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(ARL Project No. 39.018-026)

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DEVELOPMENT OF HEAT-TREATED COMPOSITE STEEL ARMOR (U)

FINAL TECHNICAL REPORT

By

S. J. Manganello
G. C. Carter

DDC RECEIVED AUG 22 1967

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Prepared By

UNITED STATES STEEL CORPORATION
APPLIED RESEARCH LABORATORY
MONROEVILLE, PENNSYLVANIA

Under
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FINAL TECHNICAL REPORT **AMRA CR 66-08/3(F)**

(ARL Project No. 39.018-026)

By

S. J. Manganello
G. C. Carter

Approved By

A. M. Rathbone

July 7, 1967

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SECRET

FOREWORD

This report was prepared by the Applied Research Laboratory of United States Steel Corporation under U. S. Army Contract No. DA-19-066-AMC-336(X); OI-19-066-D6-01885(X). The contract was administered under the U. S. Army Materials Research Agency, Watertown, Massachusetts, with Mr. Dino J. Papetti serving as technical supervisor. This is the final report and covers work conducted from May 19, 1966 to May 19, 1967.

ABSTRACT

A research program was conducted to develop and optimize lightweight heat-treatable composite steel armor for protection against caliber 0.30 and 0.50 AP M2 projectiles. Metallurgical, mechanical, and ballistic evaluations of plate composites indicated that (1) low-alloy (Ni-Cr-Mo) steels with about 0.55 percent C (front face) and 0.30 percent C (rear face) metallurgically bonded strongly in layer-thickness proportions of about 50 percent front-50 percent rear (caliber 0.30 plates) or 40 percent front-60 percent rear (caliber 0.50 plates) and heat-treated by quenching and tempering to hardnesses of about 60 Rockwell C (front) and 50 Rockwell C (rear) exhibited merit ratings of about 1.4; (2) higher merit ratings were obtained against caliber 0.30 projectiles than against caliber 0.50 projectiles; (3) higher merit ratings were obtained in production plates than in laboratory plates; (4) multilayer composites, although generally tougher, were no better than 2-layer composites in resistance to penetration by AP projectiles, and (5) a shear-compression specimen effectively measured the bond strength of dual-hardness steel plate composites.

Seven production-size lots of roll-bonded dual-hardness steel armor have been made on existing facilities. Several large plates were supplied to AMRA. Production controls necessary to meet (or approach) the requirements in Specification MIL-S-46099A were determined.

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INTRODUCTION

Objective

The purpose of this research program was to develop and optimize lightweight heat-treatable composite steel armor for protection against caliber 0.30 and 0.50 AP M2 projectiles. It was aimed at producing armor materials with a merit rating of 1.5 or greater that could be produced in commercial quantities at moderate cost on existing equipment.

Background

Research studies by AMRA, Philco Corporation, and others[1,2,3]* resulted in the development of ausformed (thermo-mechanically worked) dual-hardness (or dual-property) steel armor capable of providing about 50 percent greater ballistic protection against caliber 0.30 and 0.50 armor-piercing projectiles than did homogeneous specification steel armor (MIL-S-12560B) of the same thickness (areal density), and multi-hit capability not afforded by ceramic composites. Since 1964, U. S. Steel has been conducting research to develop heat-treatable composite steel armor. Preliminary studies indicated that a good metallurgical bond was required between the individual steel plates, that front-plate decarburization was detrimental to ballistic properties, and that merit ratings of about 1.5 could be attained against caliber 0.30 armor-piercing projectiles. However, the effects of chemical, metallurgical, and mechanical variables on the ballistic performance of heat-treatable steel composites had not been investigated. Therefore, significant improvements in ballistic performance and processing controls were believed to be possible with additional research. Consequently, U. S. Steel entered into a contract with AMRA on May 19, 1966, to conduct research and development studies on heat-treatable light-weight composite steel armor.

Scope of Work

Studies were conducted at the Applied Research Laboratory to evaluate two-layer steel composites produced by the following techniques:

1. Roll bonding.
2. Roll and diffusion bonding.
3. Explosion cladding.

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*See Literature Cited.

4. Explosion cladding and rolling.
5. Cast cladding and rolling.
6. Weld overlaying and rolling.

In addition, multilayer steel composites produced by roll-bonding techniques were evaluated.

Some of the variables that were investigated in this study were:

1. Composition, heat treatment, and hardness of component steels.
2. Total thickness and thickness proportions of component plates.
3. Type and quality of metallurgical bond.
4. Surface condition.
5. Factors affecting plate flatness.

In addition, mechanical-testing techniques for measuring the bond strength and toughness of composite steel armor were investigated.

Seven production-size lots of dual-hardness steel armor have been successfully made on existing facilities, thereby demonstrating the feasibility of manufacturing this armor on a production basis. Valuable production and specification information was developed, partly as a result of this research contract, and partly as a result of a related supply contract ("educational order"), Contract No. DA-19-066-AMC-351(X); OI-19-066-D6-02214(X). As part of the present research contract, ten large plates from a production lot will be supplied to AMRA for ballistic evaluation.

This final report, which is classified SECRET, describes the research work conducted during the period May 19, 1966 to May 19, 1967, on Contract No. DA-19-066-AMC-336(X); OI-19-066-D6-01885(X) with the U. S. Army Materials Research Agency.

ARMOR COMPOSITION DEVELOPMENT

Available Steels

Research conducted during the past four years has shown that several low-alloy homogeneous armor steels containing from 0.25 to 0.60 percent carbon, 0.25 to 0.85 percent manganese, 0 to 3 percent nickel, 0.40 to 1.50 percent chromium, 0.25 to 0.75 percent molybdenum, and 0 to 0.10 percent vanadium and heat-treated

to relatively high hardness levels, exhibited resistance to penetration by armor-piercing projectiles superior to that of specification (MIL-S-12560B) steel armor. Therefore, many of these steels were considered logical candidates as components of dual-hardness or composite steel armor. Table I lists the compositions of a number of these promising steels (Steels 1 through 8) as well as those of other steels that were available at the Laboratory and that were considered likely candidates for armor steels. Steels 1 through 8 are laboratory steels, and Steels 9 through 23 are production steels. Steels 9, 10, 20, 21, 22, and 23 are components of production dual-hardness steel plates (from 3 of the 7 aforementioned production lots). All the steels in Table I were available as 3/4- to 3-inch-thick plates, and thus were thick enough to be roll-bonded.

Experimental Armor Steels Made at the Laboratory

Table II lists the compositions of 24 experimental armor steels that were evaluated at the Laboratory. Except for Steels S, T, U, and V (high-silicon steels), the steels were selected so that low austenitizing temperatures could be employed in the hardening treatment. Austenitizing at relatively low temperatures generally promotes fine grains, the smallest amount of retained austenite, the least distortion during quenching, the least susceptibility to quench cracking, and optimum toughness.

Except for Steels Q and R, which were vacuum-melted as 300-pound induction-furnace heats, the steels were air-melted as 500-pound induction-furnace heats and rolled to 2-inch-thick plates, after which a small part of most plates was cross-rolled to 1/2-inch-thick plates. Gradient-furnace studies, hardness tests, and quench-cracking studies were conducted on the 1/2-inch-thick plates, and the amount of retained austenite in most of the hardened steels was determined.

Steels A, B, C, D, E, J, and N are 0.75Mn, 1.00Ni, 0.50Cr, 0.50Mo steels with variations in carbon content from 0.33 to 0.49 percent. These steels were evaluated initially to determine the lowest carbon content (for weldability considerations) at which steel of this general composition could be safely water-quenched, without quench cracking, to a minimum hardness of about 60 Rockwell C. (Water-quenching facilities for large plates were available in a number of steel plants, but similar oil-quenching facilities for plates were not generally available.) Steels F and G are water-hardening (AISI W-5) and oil-hardening (AISI 52100) 1 percent carbon steels, respectively, that were evaluated as very-high-hardness front-plate steels in composites consisting of two or more layers. Steels H and I are D6A steel and a lower molybdenum modification of D6A steel, respectively, that were evaluated as front- or intermediate-plate steels in composites. Steels K, L, and M are modified AISI 6140

(Cr-V) steels for possible application as front- or intermediate-plate steels in composites. The addition of chromium and vanadium was believed to increase the hardness attainable at a given carbon level and also to retard the rate of formation and the amount of scale and decarburization. Steels O and P are "ultra-service steels" that were vacuum-melted using the best low-residual practice currently known to produce maximum toughness. Steels Q and R are the components of roll-bonded composites that were to be evaluated both as heat-treated and as ausrolled armor. Steels S, T, U, and V are components of composites that contain (1) high amounts of manganese, silicon, and/or chromium to increase bainite hardenability, (2) vanadium and columbium additions to refine the grain size, and (3) high-silicon to permit tempering at temperatures higher than 300 F. Studies were conducted on composites consisting of Steels S, T, U, and V to determine the effect of solution, morphology, and distribution of carbides on ballistic performance. Also, it was thought that the presence of increased amounts of silicon and of carbide formers in these four steels might increase elevated-temperature strength and thus increase resistance to adiabatic shear.

Heat-Treating Studies

Table III lists the calculated upper and lower critical temperatures (Ae_3 and Ae_1, respectively) and the calculated martensite-start (M_s) temperatures of all the steels in Tables I and II except the three maraging steels (Steels 16, 17, and 18) and Steels J3 and N3, which were intended to have the same composition as Steels J and N, respectively. Actually, the carbon contents of Steels J3 and N3 were slightly lower than those of Steels J and N. These calculated temperatures were used as an initial guide in the heat treatment of the armor steels.

The results of gradient-furnace studies on the carbon series (Steels A, B, C, D, E, J, and N), Table IV, indicate that a minimum hardness of 60.5 R_C was attained in the as-water-quenched steels containing 0.41 percent or more carbon, but that relatively low austenitizing temperatures were required to eliminate quench cracking on water quenching. For example, austenitizing temperatures would have to be 1410 F or lower for Steel J (0.49% C), 1590 F or lower for Steel E (0.44% C), and 1675 F or lower for Steel D (0.41% C) to avoid quench cracking on water quenching. Quench cracking was encountered in some subsequently produced plate composites containing steels with greater than 0.43 percent carbon that were water-quenched from about 1500 F.

The plot of carbon content versus hardness, Figure 1, indicates that a carbon content of about 0.47 percent would be necessary to obtain a hardness of 60.5 R_C after oil quenching, and a carbon content of about 0.32 percent (extrapolated) would be necessary to obtain a hardness of 51.0 R_C after oil quenching. (Tempering at temperatures of 250 F to 300 F would lower these hardnesses about 2 Rockwell C.) The lower hardness (approximately 3 Rockwell C) for the oil-quenched specimens compared with the water-quenched specimens was not believed to be caused by a deficiency of hardenability in the base steel, but rather to self-tempering that occurs during oil quenching (oil-quenched steel cools very slowly through the martensite-transformation region, particularly if the oil temperatures rises). The ideal plate thicknesses (L_I) for 95 percent martensite are 1.7 inches for Steel N (0.33% C) and 2.0 inches for Steel J (0.49% C); thus a nominal 1/2-inch-thick plate could be water-quenched readily to 95 percent martensite. Examination of isothermal-transformation (IT) diagrams for steels with compositions similar to that of Steel C (0.40% C) indicated that these base steels should have adequate hardenability to oil-quench essentially to martensite in 1/2-inch-thick plate. (Since the time this heat-treating study was conducted[8]) quenching with glycol-water solutions has become more widespread than oil quenching, and the quenching power of glycol-water solutions is somewhat greater than that of oil.[9]))

The steels containing 0.44 and 0.49 percent carbon (Steels E and J) exhibited only 5 percent retained austenite when water-quenched from 1500 F, and 6 and 8 percent, respectively, when oil-quenched from 1500 F, Table V. Overall results of retained austenite determinations on Steels A, B, C, D, E, J, and N indicated that 2 to 7 percent retained austenite was present in the microstructures of as-quenched (from 1500 F) 1/2-inch-thick plates, and that single or double tempering at 250 F (followed by water quenching) did not significantly change this amount.

As will be discussed in a later section, the ballistic limits of water-quenched and tempered composites were higher than those of oil-quenched and tempered composites of the same material, even though some of the water-quenched plate composites contained quench cracks in the front layer. The amount of retained austenite in the specimens was believed to be a primary cause of this difference in ballistic performance. Therefore, the amount of retained austenite was determined on duplicate specimens cut from ballistically tested plates of 2-, 3-, and 4-layer composites that had been water-quenched and oil-quenched. Because it was

thought that sample-preparation technique might influence the amount of retained austenite measured by X-ray diffraction techniques, duplicate metallographic specimens were both abrasively polished on billiard cloth and electrochemically polished prior to austenite determination of the front-face steel. The results of this study are shown in Table VI, and indicate that no significant differences in the amount of retained austenite resulted from the two different methods of sample preparation. However, as would be expected, the amount of retained austenite was greater in the high-carbon steels than in the low-carbon steels and less in the water-quenched plates than in the oil-quenched plates.

Gradient-furnace studies and other heat-treating studies were conducted to determine the best austenitizing temperature for each steel listed in Table II. On the basis of the lowest austenitizing temperature that would provide high hardness after oil and/or water quenching, optimum temperatures that ranged from about 1450 to 1650 F, Table VII, were selected.

Composites Evaluated

Over 170 armor composites were ballistically tested during the present contract work. Of this total, about 120 composites were experimental (Laboratory) composites, whereas the remainder were plate samples from the first three production lots of dual-hardness steel armor made at U. S. Steel Corporation. The compositions of the component steels from each of the composites (with the exception of the weld-overlay materials) are shown in Tables I or II. Throughout this report, the plate composites are identified by hyphenated numbers and letters according to their component-steel codes in Tables I and II, with the front (hard) layer being the first digit(s) and the rear ("soft") layer being the last digit(s). For example, Composite D-3 is a two-layer composite of Steel D as the front-face material and Steel 3 as the rear-face material. For tricomposites (3 layers) and quadcomposites (4 layers), the identity of each plate composite follows the same layer sequence with the front-layer steel being the first digit(s), the next layer the second digit(s), etc.

Composites were produced by each of the six techniques mentioned in the Introduction. Each of these techniques is discussed separately in this report. All but two of the multilayer composites (Composites 9-10-13) were produced by roll-bonding techniques.

ARMOR PROCESSING DEVELOPMENT

Effect of Front-Plate/Rear-Plate Thickness Proportions

Plate composite material, 0.7-inch thick, from the first production trial of dual-hardness armor (Composite 9-10, Pack 65F) was cut into fourteen 5-1/2- by 10-inch plate samples, diffusion-treated for 1-1/2 hours at 2075 F in a dry helium atmosphere to improve the bond strength, then Blanchard-ground on both surfaces to nominally 0.305-inch-thick plate samples (11 samples) with front-plate to rear-plate thickness proportions (in percent) from 0/100 to 100/0. The plate samples were oil-quenched from 1500 F, double-tempered at 250 F, lightly hand-ground to nominally 0.300-inch-thick, and tested at AMRA with caliber 0.30 armor-piercing projectiles at 0^{o} obliquity. The remaining three plate samples were ground to a final nominal thickness of 0.500 inch so as to produce front-plate to rear-plate thickness proportions (in percent) of 35/65, 45/55, and 60/40, then hardened; these samples were tested with caliber 0.50 armor-piercing projectiles at 0^{o} obliquity. The details on these 14 plate samples of Composite 9-10 and the ballistic-test results are listed in Table VIII, A and B.

The effect of the front-plate to rear-plate thickness proportions on the V_{50} protection ballistic limit is plotted in Figure 2, and the effect on the merit rating is plotted in Figure 3. Both plots illustrate that the optimum front-to-rear thickness proportion lies in the range 35 percent front-65 percent rear to 65 percent front-35 percent rear, as has been previously reported.[2)] The data for caliber 0.50 projectiles is not conclusive because too thin a plate sample (too low an e/d ratio) was tested.

To accurately determine the best thickness proportion for caliber 0.50 projectiles, plate-composite samples about 0.640-inch thick were prepared at the Laboratory as follows. Two 2.9-inch-thick plates of Steel 22 (0.54% C) and two 3.9-inch-thick plates of Steel 21 (0.31% C) were prepared for roll bonding. A 12-inch by 18-inch sandwich consisting of the high-carbon steel and the medium-carbon steel was roll-bonded (by cross-rolling) to a plate composite 1.44 inches thick, and a second similar 12-inch by 10-inch steel sandwich was roll-bonded to a plate composite 1.20 inches thick. Ten 9-inch by 11-inch samples were cut and individually Blanchard-ground on both surfaces to nominally 0.640-inch-thick plate samples, except for one sample that was ground to 0.678-inch thick. The ground samples had front-plate to rear-plate thickness proportions (in percent) in the range 0/100 to 70/30. The plate samples were austenitized at 1500 F, spray-quenched with a glycol-water solution, tempered at 275 F, lightly hand-ground, and tested with

caliber 0.50 armor-piercing projectiles at 0° obliquity. The details on these 10 plate samples of Composite 22-21 and the ballistic-test results are listed in Table VIII-C. The effect of the front-plate to rear-plate thickness proportions on the V_{50} protection ballistic limit is plotted in Figure 4, and the effect on the merit rating is plotted in Figure 5. These plots indicate that optimum performance against the caliber 0.50 AP M2 projectile was exhibited at front-plate-to-rear-plate thickness proportions of 20/80 percent to 60/40 percent, peaking at about 40/60 percent.

As little as 5 percent hard (60.0 R_C) front face was capable of effectively breaking up the caliber 0.50 AP M2 projectile, as is illustrated in Figure 6;* at a velocity of 2387 fps, the projectile achieved a partial penetration. Figures 7 and 8 are high-speed (9,000 to 20,000 frames per second) motion (rotating-prism, high-illumination) photographs of two complete penetrations and two partial penetrations, respectively. The complete penetrations are representative of the plate composite with a 15 percent front-85 percent rear layer thickness proportion (Photographs 1 and 2); Photograph 3 is of a partial penetration on the same plate composite; Photograph 4 is of a partial penetration on the plate composite with a 5 percent front-95 percent rear layer thickness proportion. These photographs confirm the observation illustrated in Figure 6 that the caliber 0.50 AP M2 projectile is being broken into small pieces when it encounters the hard front face of the heat-treated dual-hardness steel armor. Interestingly, it has been observed that higher velocity projectiles are not broken into pieces as small as the pieces from lower velocity projectiles.

A corollary objective of the study of layer-thickness proportions was to determine whether any trends in bowing tendencies existed during the heat treatment of the 0.640-inch-thick plates. No trends could be detected; however, the plate composite with a 5 percent front-95 percent rear layer thickness proportion showed no signs of bowing. Unfortunately, such a layer-thickness proportion in a dual-hardness steel plate composite would not result in optimum ballistic protection.

<u>Roll-Bonded Composites</u>

<u>Laboratory-Roll-Bonded 2-Layer Plate Composites Tested With Caliber 0.30 AP M2 Projectiles</u>. Fourteen roll-bonded 2-layer plate composites ranging in thickness from 0.265 to 0.320 inch were processed at the Laboratory and tested with caliber 0.30 AP M2 projectiles at 0° obliquity. Pertinent information

*The fragments from the projectile were recovered from cellutex boards that surrounded the front of the plate sample.

on these dual-hardness steel composites is shown in Table IX-A. Represented are average-quality (induction-furnace) steels, steels made to open-hearth quality (Composites J3-N3) with high sulfur, and steels made to ultraservice quality (Composite O-P) with low-residual content. For the most part, the differences in steel quality had little effect on the resistance of the plate composites to penetration. Except for the ultraservice-quality plate sample (Composite O-P) which was not strongly bonded and thus exhibited a merit rating of only 1.29, the roll-bonded 2-layer Laboratory plate composites exhibited merit ratings from 1.33 to 1.56.

Composite F-A (1.00% C front face-0.34% rear face) delaminated at the bondline during ballistic testing. The microstructure at the bondline consisted of a thick layer of oxides that resulted from preheating the sandwich pack to 900 F prior to peripheral welding; this preheat caused the mating surfaces to oxidize (with various temper colors).* As will be discussed subsequently, composites with a front face of Steel G (0.96% C) exhibited front spalling but did not completely delaminate at the bondline. Because most of the sandwich packs of the "G-series" were preheated to temperatures of about 500 F prior to peripheral welding, a thinner layer of oxides formed at the bondline than in Composite F-A. These experiments indicate that composites made up of steels with greater than about 0.60 percent carbon (which require preheating before welding) should either be preheated and welded in a protective atmosphere or should be preheated in air to as low a temperature as possible, preferably under 500 F.

Several of the plate composites (particularly thicker plates that were tested with caliber 0.50 AP M2 projectiles) were water-quenched from the austenitizing temperature rather than oil-quenched to achieve a higher front-face hardness. In some of these plate samples (notably the "J-series"), the front (high-carbon) face quench-cracked before ballistic testing; in some cases, these cracks progressed through the plate during ballistic testing. Steels J, K, and 6 quench-cracked when water-quenched from the austenitizing temperature—these steels contained 0.49 to 0.57 percent carbon.

Figure 9 illustrates the ballistic behavior of Composite D-3. The ballistic performance of this dual-hardness plate composite was excellent, and its merit rating (1.41) would probably have been

*To prevent cracking associated with peripheral welding of the sandwich packs (with austenitic stainless-steel covered electrodes in air), composites made up of steels with greater than about 0.60 percent carbon had to be preheated to temperatures in the range 450 to 900 F.

above 1.5 had the front plate been slightly harder (that is, if the carbon content of the front plate had been slightly higher than 0.41 percent.

Laboratory-Roll-Bonded Multilayer Plate Composites Tested With Caliber 0.30 AP M2 Projectiles. Fifteen roll-bonded 3-layer plate composites ranging in thickness from 0.283 to 0.317 inch and and three roll-bonded 4-layer plate composites ranging in thickness from 0.305 to 0.325 inch were processed at the Laboratory and tested with caliber 0.30 AP M2 projectiles at 0° obliquity. Pertinent information on these multilayer steel composites is shown in Tables IX-B (3 layers) and Table IX-C (4 layers). The three-layer plate composites exhibited merit ratings of 1.26 to 1.40 (except for a 1.11 merit rating for Composite F-C-1, which had a low front-plate hardness). The 4-layer plate composites exhibited merit ratings of 1.33 to 1.39. Composites with front faces comprising as little as 15 percent of the total plate thickness generally performed as well as composites with front faces comprising 40 percent of the plate thickness.

These ballistic data indicate that 3- and 4-layer plate composites do not exhibit caliber 0.30 V_{50} protection ballistic limits any higher than those of 2-layer plate composites. Variations in layer hardnesses and layer-thickness proportions among the multlayer composites generally had only a slight effect on the ballistic limit.

Laboratory Roll-Bonded 2-Layer Plate Composites Tested With Caliber 0.50 AP M2 Projectiles. Seventeen roll-bonded 2-layer plate composites ranging in thickness from 0.543 to 0.655 inch were processed at the Laboratory and tested with caliber 0.50 AP M2 projectiles at 0° obliquity. Pertinent information on these dual-hardness steel composites is shown in Table X-A. Represented are average-quality (induction-furnace) steels, steels made to open-hearth quality (Composites J3-N3) with high sulfur, and steels made to ultraservice quality (Composite O-P) with low-residual content. These differences in steel quality were found to have little effect on the resistance of the plate composites to penetration. Unfortunately, the ultraservice-quality plate sample (Composite O-P) was not strongly bonded and separated at the bondline after 3 projectile impacts. The roll-bonded 2-layer Laboratory plate composites exhibited merit ratings of 1.11 to 1.33*. Two of the lowest merit ratings (1.11 and 1.18)

*Higher merit ratings were obtained in production plate composites.

were obtained by Composites S-T and U-V. These composites consisted of steels with high silicon and large amounts of carbide formers and exhibited back spalls up to 4-1/4 inches in diameter.

Figure 10A illustrates the front spalling and separation at the bondline that occurred, after 2 projectile impacts, in Composite G-11, one of the composites with an 0.96 percent carbon front face. As mentioned previously, such composites had to be preheated to high temperatures during the assembly of the sandwich packs and therefore contained a layer of oxides at the interface. Composite F-A (1.00% C front face-0.34% C rear face) completely delaminated at the bondline after only one projectile impact. Figure 11A shows that the microstructure at the bondline of this weakly bonded plate composite consisted of a thick layer of oxides that resulted from preheating the sandwich pack to 900 F prior to peripheral welding.

Figure 10B illustrates large back spalls that were observed in Composite J3-N3 (composed of high-sulfur steel components) that was rolled "cold" (in the range 1750 to 1500 F) during roll bonding.

Figure 11B, C, and D illustrates typical bonds obtained in suitably bonded Laboratory composites.

Figure 12 shows the rear-face appearance of Composite J3-N3 after oil quenching and tempering (Figure 12A) and after water quenching and tempering (Figure 12B). Although both plate composites exhibited satisfactory ballistic limits (merit ratings of 1.28 to 1.33), the water-quenched plate sample exhibited cracking through the rear face. As mentioned previously, several of the plate samples that were water-quenched from the austenitizing temperature had quench cracks in the front (high-carbon) face (notably Steels J, K, and 6). In some cases, such as that shown in Figure 12B, the quench cracks progressed through the plate during ballistic testing.

<u>Laboratory Roll-Bonded Multilayer Plate Composites Tested With Caliber 0.50 AP M2 Projectiles.</u> Fifteen roll-bonded 3-layer plate composites ranging in thickness from 0.526 to 0.587 inch and four roll-bonded 4-layer plate composites ranging in thickness from 0.542 to 0.590 inch were processed at the Laboratory and tested with caliber 0.50 AP M2 projectiles at 0° obliquity. Pertinent information on these multilayer steel composites is shown in Table X-B (3 layers) and X-C (4 layers). The 3-layer plate composites exhibited merit ratings of 1.20 to 1.32, and the 4-layer plate composites exhibited merit ratings of 1.22 to 1.30. Composites with front faces comprising as little as 15 percent of the total plate thickness generally performed as well as composites with front faces comprising 40 percent

of the plate thickness. Front layers as thin as 15 to 20 percent of the total plate thickness were thick enough to break up the core of the armor-piercing projectiles, provided that the hardness of the front face was about 59 Rockwell C or harder.

Figures 13 and 14 illustrate two tricomposites (Composites K-L-N and 6-E-13) that exhibited satisfactory ballistic performance, and Figure 15 illustrates a quadcomposite (Composite G-J-B-13) that also performed satisfactorily. Figure 16 illustrates typical bonds obtained in the roll-bonded multilayer Laboratory composites. Note that some oxides are again visible at the interface next to the 0.96 percent carbon steel (Steel G), Figure 16B.

The caliber 0.50 ballistic limit of a given bicomposite, tricomposite, or quadcomposite that was water-quenched and tempered was generally higher than that of the corresponding composite that was oil-quenched and tempered even though some of the water-quenched plate composites contained quench cracks in the front layers. The relatively poor ballistic performance of the oil-quenched plates may have resulted from the presence of (1) bainite caused by insufficient bainite hardenability, (2) self-tempered martensite caused by slow cooling below the M_s temperature in the warm oil bath, and/or (3) slightly larger amounts of retained austenite. The recent change from immersion oil quenching to spray quenching with glycol-water solutions (with greater quenching power) should eliminate some of these possible microstructural factors.

As with composites tested with caliber 0.30 projectiles, 3- and 4-layer plate composites did not exhibit caliber 0.50 V_{50} protection limits any higher than those of 2-layer plate composites. Variations in layer hardnesses and layer-thickness proportions among the multilayer composites generally had only a slight effect on the ballistic limit. Although the multilayer plate composites did not exhibit more resistance to penetration than did the 2-layer plate composites, the multilayer composites did offer better resistance to through-thickness cracking (by blunting and arresting the cracks advancing from the front face), and they generally exhibited better rear-face performance (because softer and tougher steels could be utilized for this component).

Steel F (water-hardening AISI W-5 tool steel) exhibited erratic front-plate hardness, ranging from 30.0 to 62.0 Rockwell C; Figure 17A illustrates the front cratering that was occasionally encountered in the ballistic plate samples

of this "soft" steel. Figure 17B illustrates rear-face petaling that was occasionally encountered in Steel 13; this was believed to be caused by the rear face being too soft (39.0 R_C).

Of the steels investigated in the laboratory program, Steels J, K, 6, and 7 exhibited the best front-plate performance, and Steels A, N, 2, 11, 12, and 13 the best rear-plate performance.

Production-Roll-Bonded Plate Composites Tested With Caliber 0.30 AP M2 Projectiles. Twenty-seven samples from production plate composites of dual-hardness steel armor ranging in thickness from 0.224 to 0.410 inch have been tested with caliber 0.30 AP M2 projectiles at 0° obliquity. The plate samples represented the first three production runs made by U. S. Steel Corporation. Typical bonds obtained in these roll-bonded production plate composites are illustrated in the photomicrographs in Figure 18. Merit ratings obtained on these 2-layer plate-composite samples ranged from 1.30 to 1.71; several plate samples exhibited merit ratings greater than 1.5. Plates thinner than about 0.3 inch (with e/d ratios slightly less than 1) generally exhibited higher merit ratings than slightly thicker plates (with e/d ratios slightly greater than 1). For example, a 0.224-inch-thick plate sample (Composite 20-21) exhibited a merit rating of 1.71.

The relation between plate thickness and V_{50} protection ballistic limit for the 27 production plate samples is plotted in Figure 19. Except for five plates known to be poorly bonded (solid points), the points fell within a band wherein the ballistic limit increased almost linearly as plate thickness increased. The five poorly bonded samples had the lowest ballistic limits for a given plate thickness. The average-performance (dashed) line indicates that an 0.33-inch-thick dual-hardness steel plate should defeat a caliber 0.30 AP M2 projectile at muzzle velocity, and that an 0.31-inch-thick similar plate should defeat this projectile at 50 yards.

Figure 20 summarizes the ballistic performance obtained to date on armor steels produced in the Laboratory or in the plant. Against caliber 0.30 AP M2 projectiles at 0° obliquity, the "best" high-hardness homogeneous armor steels exhibited merit ratings in the range 1.20 to 1.35, whereas the "best" dual-hardness composite steel armors exhibited merit ratings in the range 1.50 to 1.70.

Production-Roll-Bonded Plate Composites Tested With Caliber 0.50 AP M2 Projectiles. Twenty-five samples from production plate composites of dual-hardness steel armor ranging

in thickness from 0.459 to 0.637 inch have been tested with caliber 0.50 AP M2 projectiles at 0° obliquity. The plate samples represented the first three production runs made by U. S. Steel Corporation. (Other production runs have since been made.) Merit ratings obtained on these 2-layer plate-composite samples ranged from 1.20 to 1.37.

The relation between plate thickness and V_{50} protection ballistic limit for these 25 plate samples is plotted in Figure 21. Although production plates have been found to exhibit slightly higher ballistic limits than laboratory plates, no merit ratings over 1.40 have yet been obtained, even in production plates, against caliber 0.50 armor-piercing projectiles. However, as indicated in Figure 21, progressive improvements in ballistic performance are being obtained with each successive production run of dual-hardness steel armor.

Table XI lists the performance of production plates of dual-hardness steel armor against caliber 0.50 AP M2 projectiles at 45° obliquity. At this obliquity, dual-hardness armor is only slightly superior to MIL-S-12560B (specification) steel, exhibiting merit ratings of about 1.15. The data in Table XI indicate that a dual-hardness steel plate with a thickness of about 0.420 inch will defeat a muzzle-velocity caliber 0.50 AP M2 projectile at 45° obliquity.

Roll Bonding Versus Roll and Diffusion Bonding

To determine whether a high-temperature diffusion treatment after rolling was required to obtain satisfactory bonds, bonds obtained by roll bonding and by roll and diffusion bonding were compared. Figure 22 illustrates the bonds that were obtained in Composite 9-10 (Production Pack 65D) after rolling followed by a high-temperature diffusion treatment as compared with that in the as-rolled product. The microstructures of the unhardened and hardened specimens indicate that good bonds were obtained in the as-rolled (12 to 1 rolling reduction) plate composite but that slightly better appearing bonds were obtained in the as-rolled and diffusion-treated plate composite. However, the high-temperature diffusion treatment, which was conducted in an air atmosphere, caused excessive scaling and decarburization and an undesirable hardness gradient through the plate thickness.

Two other similarly produced plate composites from Composite 9-10 (Production Pack 65G) were ballistically tested by AMRA. Sample 17 had been roll-bonded (about 12 to 1 rolling

reduction), whereas Sample 16 had been similarly roll-bonded and diffusion-treated by heating to 2075 F for 1-1/2 hours in a dry helium atmosphere after rolling. Both samples were than oil-quenched from 1500 F and double-tempered at 250 F to a front-plate hardness of 62 Rockwell C and a rear-plate hardness of 52.5 to 53.0 Rockwell C. The roll-bonded and the roll- and diffusion-bonded plate composites were then ground to a thickness of about 0.3 inch and tested with caliber 0.30 AP M2 projectiles at 0° obliquity. The ballistic-test results, Table IX-D, indicate that the ballistic properties of the roll-bonded and of the roll- and diffusion-bonded composites were similar; in fact, the ballistic limit of the roll-bonded composite (Sample 17) was slightly superior to that of the roll- and diffusion-bonded composite (Sample 16).*

These data indicate that a high-temperature diffusion treatment after rolling is not required to obtain satisfactory bonding in composites of similar steels that have been reduced a large amount during roll bonding. However, it is recommended that composites reduced less than about 5 to 1 during roll bonding should be diffusion-treated either during or after rolling, with measures being taken to minimize scaling and decarburization. Diffusion treating in this manner may also be desirable in composites in which an interlayer of metallic sheet or foil is utilized to accomplish or enhance bonding.

Explosion Cladding and Rolling

Studies were conducted to determine whether explosion cladding and/or explosion cladding followed by rolling could be employed to satisfactorily bond plates of dual-hardness steel armor. The explosion-cladding experiments were conducted at no cost to the government in a cooperative program with U. S. Steel, by E. I. DuPont de Nemours and Company, Gibbstown, New Jersey, under the technical direction of Dr. S. S. Tör.

Laboratory-produced plates of Steels J (0.49% C) and N (0.33% C) in nominal thicknesses of 0.16, 0.44, and 0.82 inch were normalized (grain-refined), tempered (softened), and Blanchard-ground flat on the intended mating surfaces to a 63 microinch (RMS) maximum finish. The plates were 11-1/2 inches by 24-1/2 inches except for the 0.82-inch-thick plates, which were 14 inches by 23

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*The 0.3- and 0.5-inch-thick plates of Composite 9-10 evaluated in the layer-thickness-proportion study were also roll- and diffusion-bonded, as was Tricomposite 9-10-13.

inches. The plates were sent to duPont's Gibbstown, New Jersey facility where the Steel N (0.33% C) plates were driven, by explosive force, into the Steel J (0.49% C) plates to achieve cladding. In this manner, duplicate composites with total thicknesses of 0.32, 0.88, and 1.63 were produced. All composites were explosively clad without difficulty. Figure 23 illustrates the appearance of the two 0.32-inch-thick explosively clad (not subsequently rolled) plate composites. The nonbonded areas around the edges are indicated. The thicker (0.88- and 1.63-inch-thick) plate composites exhibited more nonbonded areas around the edges than the thin (0.32-inch-thick) plate composites, as would be expected because of the size effect.

Oil-quenched and tempered plate samples from the two explosively clad (not subsequently rolled) 0.32-inch-thick composites (Composites J-N(XA) and J-N(XB) were ground to 0.302-inch-thick plates and ballistically tested with caliber 0.30 AP M2 projectiles at AMRA. The ballistic-test results are listed in Table IX-E, and show that these composites had merit ratings of 1.30 to 1.38. The plate composites were bonded strongly enough so that separation did not occur at the bondline during ballistic testing. Figure 24 illustrates the appearance of the plates after ballistic testing with caliber 0.30 AP M2 projectiles. The microstructure of the bond of the explosively clad 0.302-inch-thick plate composites is shown in Figures 25A and B. It is noteworthy that the metallic jet visible at the bondline of the as-clad plates, Figure 25A, was almost completely obliterated after the hardening treatment, Figure 25B.

The duplicate 0.88- and 1.63-inch-thick composites of Steels J and N that were explosively clad by duPont were rolled (each composite thickness) in the temperature range 2150 to 1700 F to 0.40- and 0.66-inch-thick plates, ground to thicknesses of approximately 0.32 and 0.58 inch, oil-quenched and tempered, and ballistically tested at U. S. Steel against caliber 0.30 and 0.50 AP M2 projectiles, respectively. The ballistic-test results are listed in Tables IX-E and X-D and show that against caliber 0.30 AP M2 projectiles, Composites J-N(XD) and J-N(XF) exhibited merit ratings of 1.39 and 1.34, respectively; and against caliber 0.50 AP M2 projectiles, Composites J-N(XC) and J-N(XE) exhibited merit ratings of 1.24 and 1.19, respectively. These four explosively clad and rolled plate composites were also bonded strongly enough so that separation did not occur at the bondline during ballistic testing. Figure 26 illustrates the appearance of the plates after ballistic testing with caliber 0.50 AP M2 projectiles. The microstructure of the bond of the explosively clad and rolled 0.58-inch-thick plate composites is shown in Figures 25C and D. The hardness of the explosively clad and rolled 0.3-inch-thick plates was

slightly greater than that of the explosively clad (not subsequently rolled) plates of the same thickness.

The ballistic limits obtained for the explosively clad and the explosively clad and rolled plate composites were equivalent to those obtained for roll-bonded plate composites of the same steels and thicknesses, and probably would have been somewhat higher had the front face been harder (higher in carbon content).

A 14- by 12-inch sample of one of the explosively clad (not subsequently rolled) 1.63-inch-thick plate composites was heat-treated, ground to 1-1/2 inches thick, and ballistically tested at AMRA with 14.5 mm APl BS-41 (tungsten-carbide core) projectiles at 0^{o} obliquity. This Composite J-N (XF-1) had a merit rating of 1.11 and, although it back-spalled, did not separate at the bondline during ballistic testing, Figure 27.[10)]

The experiments on explosion cladding and explosion cladding followed by rolling have indicated that both of these methods are technically feasible methods to bond armor steels. Metallographic examination indicated that the bonds were good, and the plate composites survived the required ballistic testing without separating at the bondline.

Weld Overlaying Followed by Rolling

High-hardness weld overlaying of medium-carbon steel plates was investigated as one method of achieving metallurgically bonded dual-hardness steel composites. The procedure used was to deposit high-hardness (approximately 60 R_C after heat treating) weld metal on a medium-carbon steel plate, hot-roll the composite to the desired thickness, remove the scale and decarburized surface material, and then heat treat the weld-overlayed plate to the desired hardness (front and rear).

The first experiment was performed by using the submerged-arc welding process with hardfacing weld wire (0.46% C) and a neutral flux (containing no alloy additions). A 1/2-inch-thick by 6-inch-wide by 9-inch-long plate of Steel N (0.33% C) was shot-blasted on one surface and then tack-welded to a base plate to prevent the distortion (curling up) that occurs during the application of weld overlays to relatively thin plates. Three layers of weld metal with a total thickness of 5/16 inch were applied to the shot-blasted surface. The weld-overlayed plate was cross-rolled to a thickness of 0.40 inch and slow-cooled. Metallographic examination revealed a good bond, as shown in the representative photomicrograph in

Figure 28A. After oil quenching from 1500 F and double tempering at 250 F, the weld metal exhibited a very low hardness (31.0 R_C), and the microstructure contained a large amount of ferrite. Chemical analysis revealed that the carbon content of the weld overlay was only 0.15 percent. The cause of this loss in carbon was not determined but it was believed to be the result of the "neutral" flux being oxidizing.

Plates of Steel N were weld-overlayed with Murex Hardex 45 (0.61% C) and Murex Hardex 52 (0.58% C) covered electrodes.* After weld-overlaying (35 to 40% front face; 60 to 65% rear face), the plates were processed in the same manner as described previously. Figure 28B is a representative photomicrograph of the metallurgical bond obtained after cross-rolling to a thickness of 0.40 inch. The two plates were heat-treated to a front face hardness of 59.0 to 60.0 Rockwell C, ground to about 0.324 inch thick, and ballistically tested with caliber 0.30 AP M2 projectiles at 0° obliquity. The plate samples (Codes 4B and 5B) exhibited merit ratings of 1.40 and 1.44, respectively, Table IX-F. A photograph of the Hardex 52-overlayed and ballistically tested plate (Code 5B) is shown in Figure 29A.

Two 1/2- by 6- by 10-inch plates of Steel A (0.34% C) were Blanchard-ground on one surface and weld-overlayed with Hardex 45 and Hardex 52 covered electrodes, respectively, to a total thickness of approximately one inch (50% front face - 50% rear face thickness proportions). The weld-overlayed plates (Codes A1 and A2) were cross-rolled to a thickness of 0.66 inch, surface-ground to remove scale and decarburized material, oil-quenched from 1500 F, and tempered at 275 F. Because the two weld overlays (front faces) did not attain sufficient hardness (55.0 to 56.0 R_C), one plate (Code A2 with the Hardex 52 overlay) was re-austenitized and quenched in a glycol-water solution without subsequent tempering. The plates were ground to thicknesses of 0.525 inch (Code A1) and 0.548 inch (Code A2), ballistically tested with caliber 0.50 AP M2 projectiles at 0° obliquity, and exhibited merit ratings of 1.29 and 1.22, respectively, Table X-E. The weld-overlayed plate sample that was not tempered (Code A2) fractured into four pieces during ballistic testing. A photograph of the Hardex 45-overlayed and ballistically tested plate (Code A1) is shown in Figure 29B.

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*Several other weld metals could have been successfully used; the covered electrodes that were employed were available at the time.

Although very good metallurgical bonds and satisfactory ballistic properties were obtained in the weld-overlayed plates, the weld-overlay technique is a rather costly method for producing composite steel armor. For such a method to be considered seriously as a production technique, special automatic welding equipment capable of depositing large amounts (greater than 50 pounds per hour) of hardfacing weld metal at the minimum thickness required for good ballistic properties would be required. Such hardfacing processes and equipment have been described in the literature.[11,12,13,14] As backing (base) plate thicknesses increase, weld overlaying (as a cladding technique) reportedly becomes more economical.[14]

Cast-Cladding Followed by Rolling

Cast-cladding experiments were initiated to determine the parameters controlling bonding between high- and medium-carbon steels. Figure 30 is a sketch illustrating the basic steps that were planned for processing plate-sandwich-insert cast composites.[8] None of the three experiments conducted yielded satisfactory results.

In the experiments, 1/2-inch-thick plates of the 0.53 percent carbon steel were employed as upright centrally located mold inserts,* and the 0.31 percent carbon steel was poured around this insert. Both 500-pound air-melted and 300-pound vacuum-melted induction-furnace heats were poured at 3000 to 3050 F in preheated molds, the air-melted heats in an argon atmosphere and the vacuum-melted heats in vacuum. One of the subsequently rolled cast-clad ingots (Composite 5-N) displayed a metallurgical bond between both of the plate inserts and the cast steel, Figure 31A, but the other two casting and rolling experiments (Composites 4-N and 8-N) resulted in a lack of sound metallurgical bonding, as shown in Figure 31B. In each experiment, the seal welds around the periphery of the plate inserts melted, and the separating materials between the plates escaped and contaminated the melt.

Successful cast-cladding of dual-hardness armor would probably require preheating the plate insert as well as controlling the ratio of molten-metal-to-insert volume to achieve sound metallurgical bonding with the cast steel. Cast-cladding is difficult to achieve when approximately equal proportions of front-plate and rear-plate material are to be clad. A slab-mold insert that

*The plates were either Blanchard-ground or shot-blasted at the outer surface and were peripherally seal-welded after a separating compound and asbestos sheet had been placed between them.

occupies about 50 percent of the mold volume causes the molten steel to freeze almost immediately at the insert surface with little or no metallurgical bonding. Although this problem may be less acute when production-size molds (instead of laboratory-size molds) are employed for various commercial applications[15] involving cast cladding, the significantly different layer-thickness proportions that are normally employed in these nonarmor applications minimize this problem. Moreover, the extent of bonding and the bond strength obtained in commercial cast-clad articles are much lower than those required for armor.

A weld metal with a high melting point should be used for the peripheral seal weld when a sandwich type of mold insert is to be employed. Also, melting and pouring the heat under vacuum would provide optimum conditions for preventing the formation of oxides (on the surface of the mold insert) that are detrimental to sound metallurgical bonding; however, pouring in an inert or reducing atmosphere should be adequate.[16]

In view of the very satisfactory results obtained by roll-bonding and other methods of bonding, it is not recommended that development of cast-cladding techniques for dual-hardness steel armor be pursued further.

Effects of Miscellaneous Processing Variables

Eleven 12- by 10-inch plate samples of Composite 20-21 (Production Pack 66G) with a nominal thickness of 0.265 inch were processed in various ways to determine the effects of these processing variables on ballistic performance against caliber 0.30 AP M2 projectiles at 0° obliquity. The details and results of these studies, summarized in Table XII-A, indicate that the procedures currently being used to process dual-hardness armor (grinding both surfaces, hardening, and immediate tempering) are satisfactory, as attested by the 1.50 merit rating of Sample A1. Higher merit ratings (1.54 and 1.55) were obtained in a sample that was held for a day before tempering (Sample A2) and in a sample that was not tempered (Sample C2); both samples had higher hardness, and the sample that was held for a day at room temperature before tempering cracked badly during ballistic testing. However, the as-quenched sample did not crack.

Variations in surface-preparation techniques generally did not result in major differences in merit rating (Samples D2, D3, E2, and E3). The high merit rating obtained for Sample E3,

the sample that underwent no front plate preparation, was surprising. Efforts to reduce retained austenite by a subzero and tempering treatment (Sample F2) failed to improve the merit rating. Similarly, efforts to tie up carbon as undissolved carbides (by employing intermediate tempering treatments at 1100 F or 1290 F followed by a short-time austenitizing treatment) also failed to improve the merit rating, Samples G2 and G3; in fact, the merit rating of Sample G2 was unexplainably low.

To determine the effect of minor variations in tempering conditions on the ballistic performance against caliber 0.50 AP M2 projectiles at 0^o obliquity, five 12- by 12-inch plate samples of Composite 20-21 (Production Pack 66E) with a nominal thickness of 0.535 inch were austenitized at 1500 F, spray-quenched with a glycol-water solution, and individually tempered for 30 minutes at 275, 300, and 350 F, double-tempered at 275 F, and tempered for 4 hours at 275 F. Slight differences in yield strength (209 to 219 ksi) and insignificant differences (1.5% maximum) in the amount of retained austenite resulted from these tempering variations. However, the results of the ballistic studies, summarized in Table XIII-A, indicate that only minor differences in V_{50} protection ballistic limit (92 fps maximum difference) and in merit rating (4% maximum difference) resulted from the variations in tempering. Therefore, it is concluded that the tempering treatment currently being used for production plates of dual-hardness steel armor (single temper at about 275 F) is satisfactory.

Shot-Peening Experiments

Shot peening is a cold-working process in which the surface of a metal part is impacted with round steel shot under controlled conditions. Although shot peening is used primarily to increase fatigue life and prevent stress-corrosion cracking of metal parts, it is sometimes used to form parts or to correct their shape. When the surface of a metal has been satisfactorily peened, the resultant surface residual compressive stresses aid in preventing the formation of cracks.

To investigate the effects of shot peening and the resultant surface residual compressive stresses on the ballistic properties of heat-treated armor steel composites, three quenched and tempered 0.3- by 12- by 12-inch plate samples of Composite 9-10 (Production Pack 65G) were shot-peened by Metal Improvement Company, and a fourth similar plate was retained as a control sample. Listed below are the hardnesses of the four plates as well as pertinent observations.

Plate	Surface Peened	Hardness, R_C Front	Rear	Remarks
1	None	62.0	52.0	Plate bowed (front surface convex)
2	Front	66.0	53.0	Plate bowed (front surface convex)
3	Rear	62.0	56.5	Plate bowed (rear surface convex)
4	Both	64.0	55.0	Plate was flat

The data show a definite increase in hardness at the peened surface, and indicate that plate flatness can be controlled to some extent by shot peening. The plates were ballistically tested with caliber 0.30 AP M2 projectiles at 0° obliquity. The ballistic-test results Table XII-B, indicate that shot peening improved the resistance to penetration very slightly (increasing the merit rating from 1.46 to 1.49), probably because it also slightly increased surface hardness. However, shot peening did not significantly affect the propensity of this composite (Composite 9-10) to cracking and spalling.

Rapid-Heat-Treatment Study

Experiments were initiated during the final quarter of the contract to investigate the effects of rapid heat treatment (rapid austenitizing by induction heating to produce an ultrafine grain size) on the ballistic performance of composite steel plates. Plate samples, about 9 inches by 5 inches by about 0.640 inch, of 2-, 3-, and 4-layer composites were to be rapidly heat-treated to obtain a prior-austenite grain size of about ASTM No. 12 or finer prior to testing them with caliber 0.50 AP M2 projectiles at 0° obliquity. Starting plate condition (as-rolled versus normalized and tempered) and peak heating temperature (1475 F versus 1600 F) were to be initially investigated, and three heating and quenching cycles were to be employed. However, because of early equipment and procedural problems, this program was not completed in time. With improved techniques, encouraging ballistic results were beginning to be obtained, as witnessed by the 1.36 merit rating of Sample 67AB-9, Table XIII-B. The full potential of rapid heat treatment of composite steel armor should be explored in future studies.

Effect and Minimization of Scale and Decarburization

Studies were conducted to evaluate protective slurries, mixtures, and platings for minimizing the scaling and decarburization that normally occur during rolling and heat treating of steels.

The coatings that were tested for protection at 1500 F (the usual austenitizing temperature for dual-hardness steel plates) included 10 percent bentonite-90 percent boric acid, 20 percent chromium oxide-80 percent magnesium oxide, 40 percent chromium oxide-60 percent magnesium oxide, Metlseel A213,* Metlseel A215,* 5 percent silica sand-35 percent chromium oxide-60 percent magnesium oxide, 10 percent titanium oxide-30 percent chromium oxide-60 percent magnesium oxide, 25 percent waterglass-25 percent chromium oxide-50 percent magnesium oxide, Turco Pretreat, copper plating in thicknesses at 0.003 and 0.005 inch, and aluminum paint. In addition, several of the aforementioned coatings were tested at 2000 F (a representative hot-rolling temperature for dual-hardness steel plates).

The coatings observed to be best for protection at elevated temperatures were the chromium oxide-magnesium oxide slurries, waterglass-chromium oxide-magnesium oxide, and Turco Pretreat, a commercially-produced substance (ceramic in a solvent carrier) from Turco Products, Incorporated. Turco Pretreat was selected for coating laboratory and production plates on the basis of the ease and convenience of application—it can be painted or sprayed on the plates—and because it does not flake off during quenching, thus minimizing any contamination of the closed circulatory quenching systems that would probably be employed in heat treating dual-hardness steel armor plates. Ground plates coated with Turco Pretreat and then heat-treated exhibited satisfactory hardness (nominally 60 R_C front and 50 R_C rear) after grit-blasting or grinding the plate surfaces to remove only a few thousandths of an inch of material. (The effects of various surface conditions on ballistic performance against caliber 0.30 AP M2 projectiles were previously shown, Table XII.)

Evaluation of Mechanical Tests

A program was initiated to develop mechanical-testing techniques for determining properties such as bond strength, yield and tensile strengths, toughness, and fracture characteristics of dual-hardness steel armor. Several types of specimens (tensile, impact, bend, shear-tensile, and compression) from the first production trial of dual-hardness armor (Composite 9-10) were initially investigated.[8] Figure 32 shows each type of specimen; the specimens were macroetched with nital to reveal the front and rear layers.

As is generally known, ultrasonic testing of plate composites can detect only unbonded layers (in plates with a certain minimum thickness) where actual discontinuities exist.

*Products of Glidden Chemicals, PEMCO Division.

However, it cannot distinguish a strongly bonded composite from a moderately or weakly bonded composite that might front-shatter, spall at the bondline, or delaminate during ballistic impact. A back-spalled composite (Production Pack 65K, Composite 9-10) is illustrated in Figure 33A; in contrast, Figure 33B illustrates a strongly bonded composite (Production Pack 66B, Composite 20-21) that exhibited excellent rear-plate performance. A ballistically tested Laboratory plate sample exhibiting front spalling and separation at the bondline was previously shown in Figure 10A. These examples illustrate the desirability of evaluating the bond strength of plate composites at an early stage of production (for example, after rolling) so that excessive production costs on poorly bonded plate composites could be avoided.

Figure 34A illustrates the principle of dual-hardness composite steel armor. The cracks emanating from the hard front plate of Composite 9-10 after a projectile impact were arrested by the tougher rear plate. Figure 34B illustrates a close-up of a back spall encountered in a poorly bonded plate of Composite 9-10. The crack progressed from the front plate to the bondline, then followed the bondline, then broke through the rear plate.

To determine the bond strength of dual-hardness steel armor, a shear-compression specimen previously developed at the Laboratory[17)] and shown in Figure 35A is now being employed.[18)] Testing involves loading the specimen in compression until failure occurs by shear fracture along the bondline. To obtain valid results with this test, failure must occur along the bondline, and buckling must be avoided. Rounding the ends of the specimen (as shown in Figure 35B) helps significantly in preventing excessive bending moments from developing during testing. The shear-compression specimen is still in the development stage; therefore, data on the relative bond strengths of composites are very limited. However, preliminary data indicate that weakly to moderately bonded composites would be expected to have a shear strength at the bond (as determined with shear-compression specimens) of less than about 90 ksi, and strongly bonded composites would be expected to have a shear strength greater than about 100 ksi (2/3 or more of the shear strength of the weaker component). When valid test results are consistently obtained, extensive data will be compiled on composites known, from ballistic testing, to exhibit strong bonds and weak bonds. This information should aid in establishing a minimum bond-strength requirement for composite steel armor.

Tests are continually being conducted to determine the mechanical properties of composite steel armor. Shown below are

typical properties for heat-treated dual-hardness steel armor. All specimens were from plates that were oil-quenched from 1500 F and double-tempered at 250 F.

Steel	Plate Thickness, inch	Yield Strength (0.2% Offset), ksi	Tensile Strength, ksi	Elongation in 2 Inches, %	Reduction of Area, %
20 (0.51% C)	0.25	219	361	6	15
21 (0.31% C)	0.25	183	262	9	45
Pack 66B (Composite 20-21)	0.40	185	319	9	12

Room-temperature Charpy V-notch energy-absorption values of quenched and tempered composite steel armor range from 5 to 20 ft-lb, depending on notch orientation, with the lowest values occurring for front-face-notched specimens.

To determine the fracture characteristics of armor steels, studies are in process to determine the fracture toughness (stress-intensity factor, K_{IC}) of the individual front- and rear-face materials as well as of the bonded composites.* Initial three-point slow-bend tests performed on 7-inch-long fatigue-cracked edge-notched specimens from 1/4-inch-thick plate material (given the same heat treatment as described in the preceding paragraph) resulted in K_{IC} values of approximately 28 ksi $\sqrt{\text{inch}}$ for Steel 20 (front-face steel) and 63 ksi $\sqrt{\text{inch}}$ for Steel 21 (rear-face steel); this indicates that Steel 21 can tolerate a flaw 7-1/2 times larger than that which Steel 20 can tolerate. However, these values should be considered tentative until further fracture-toughness tests are conducted.

Additional tests may help to determine relations between yield strength, fracture-toughness (K_{IC} value), and ballistic performance.

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*Fracture toughness is a more important consideration for structural armor applications than for hang-on armor applications.

Studies to Achieve Improved Plate Flatness

To determine production controls necessary to meet (or approach) the requirements in Specification MIL-S-46099A[19] and to determine the tolerances that may be expected under normal production conditions, laboratory studies were conducted to determine the effects of quenchant spray pressure, one-sided quenching, differences in rolling direction in the plate, plate thickness, plate size, M_s-temperature mismatch, rolled-versus ground-plate surfaces, and prebowing on the bowing tendency of production dual-hardness steel plates. These studies were initiated after it was observed that large plates (48 by 73 inches) bowed more than desired or expected during quenching, (Contract No. DA-19-066-AMC-351; OI-19-066-D6-02214X). In all cases, the high-carbon layer was on the outer (convex) surface.

Although Specification MIL-S-46099A permits a maximum out-of-flatness of 7/16 inch in a 36-inch length,[19] this extrapolates to an undesirable 1.8-inch out-of-flatness in a 73-inch length or 4.7 inches in a 120-inch length on the basis that a flat plate assumes a spherical (or parabolic) contour when quenched either unrestrained or between flat (platen) dies, Figure 36. Most of the distortion is caused by the difference in volume expansion between the two steels when martensite forms.

Laboratory studies conducted chiefly with 12- by 24-inch plates that were spray-quenched with a water solution containing 20 percent UCON-A (a Union-Carbide glycol-type product) indicated that

1. A quenchant spray pressure of 7 to 12 psi (top and bottom) resulted in flatter plates than a pressure of 2 psi.

2. Quenching only the high-carbon surface or quenching both surfaces resulted in flatter plates than did quenching only the medium-carbon surface.

3. Differences in rolling direction within the plate did not significantly affect bowing tendencies.

4. Thinner plates (0.317 inch) bowed slightly more than thicker plates (0.383 to 0.582 inch).

5. Bowing was relatively more severe in small plates (4 by 8 inches) than in larger plates (up to 17 by 34 inches).

6. Differences of 54 to 161 F in the M_s temperature of the front and rear steel layers did not significantly affect bowing

tendencies; however, plates with both layers having relatively high M_s temperatures may bow more than plates with one or both layers having relatively low M_s temperatures.

7. Ground plates bowed about the same as, or very slightly less than, as-rolled plates of the same composition and thickness.

8. Tempering at 275 F (with weights on the bowed surface) slightly lessened the amount of bow that resulted in the quenched (from 1500 F) plates.

9. Plates must be prebowed a greater opposite amount (toward the medium-carbon surface) than would be indicated by the bow that normally occurs toward the high-carbon surface.

CONCLUSIONS

From the metallurgical, mechanical, and ballistic evaluations that were conducted on heat-treated composite steel armor, the following conclusions are drawn:

1. A front-face nominal composition (in percent) of 0.55C, 0.75Mn, 1.20Ni, 0.75Cr, and 0.50Mo and a rear-plate nominal composition of 0.30C, 0.75Mn, 1.20Ni, 0.75Cr, 0.50Mo have satisfactorily served as the components of lightweight, heat-treatable, dual-hardness steel armor.

2. The optimum heat treatment for the dual-hardness steel plates consisted of a low-temperature austenitizing treatment (at about 1500 F) followed by quenching (at an H value of about 0.3), followed by tempering (at about 275 F). This heat treatment resulted in a microstructure of quenched and tempered martensite and front- and rear-plate hardnesses within the scope of those in Specification MIL-S-46099A.

3. Against caliber 0.30 AP M2 projectiles at 0° obliquity, the optimum front-plate-to-rear-plate thickness proportions for roll-bonded, heat-treated dual-hardness steel armor (0.300-inch-thick plates) were in the range 35/65 percent to 65/35 percent, peaking at about 50/50 percent. Against caliber 0.50 AP M2 projectiles at 0° obliquity, the optimum

front-plate-to-rear-plate thickness proportions (0.640-inch-thick plates) were in the range 20/80 percent to 60/40 percent, peaking at about 40/60 percent.

4. The strong metallurgical bonds that were found to be required in composite steel armor were obtained by roll bonding, roll and diffusion bonding, explosion cladding, explosion cladding and rolling, and weld overlaying and rolling. Difficulties experienced in the Laboratory prevented the attainment of similar satisfactory bonds by cast cladding and rolling.

5. Multilayer plate composites (with 3 or 4 layers) did not exhibit ballistic limits any higher than those of 2-layer plate composites. Variations in layer hardnesses and layer-thickness proportions among the multilayer composites generally had only a slight effect on the ballistic limit. Multilayer composites, however, did offer better resistance to through-thickness cracking and generally exhibited tougher rear-face performance.

6. More than 170 plate samples of composite steel armor were ballistically tested. Samples from production plate composites generally exhibited better ballistic performance than samples from Laboratory plate composites. Merit ratings as high as 1.71 were obtained in production plates against caliber 0.30 AP M2 projectiles at 0° obliquity, but no merit ratings over 1.40 have been obtained against caliber 0.50 AP M2 projectiles at 0° obliquity. However, progressive improvements in ballistic performance are being made with each production run of dual-hardness steel armor made.

7. Seven production-size lots of dual-hardness steel armor have been made on existing facilities, thereby demonstrating the feasibility of manufacturing this armor on a production basis. Ten 48- by 60-inch plates for caliber 0.30 AP M2 protection (about 0.310-inch thick) and ten 48- by 60-inch plates for caliber 0.50 AP M2 protection (about 0.650-inch thick) were supplied to AMRA as part of the present contract.

8. A commercial coating that minimizes the formation of scale and the decarburization that occurs during the heat treatment of plate composites was found.

9. Through Laboratory and production studies of factors affecting plate flatness, techniques are being developed to minimize the distortion (bowing) that normally occurs during the heat treatment of composite dual-hardness steel armor. The plate composites can therefore meet the flatness requirements of Specification MIL-S-46099A.

10. A shear-compression specimen that is simple to produce from plate product and relatively simple to test on conventional equipment was found to effectively measure the relative bond strength of dual-hardness steel plate composites. Many other mechanical-testing studies were also conducted.

RECOMMENDATIONS FOR FUTURE WORK

Although significant progress was made during the one-year research program just concluded, plate composites with merit ratings greater than 1.37 for protection against caliber 0.50 AP M2 projectiles have not yet been developed. At the time the aforementioned research program was concluded (May 19, 1967), several projects to improve this ballistic performance were still incomplete. Among these projects were investigations of (1) ultraservice (low-residual, high-toughness) steels, (2) ultrafine-grained (rapidly heat-treated) versus typical-grained versus coarse-grained plate composites, (3) ausrolled and pseudo-ausrolled* plate composites, (4) surface-hardened plate composites, and (5) correlations between ballistic performance and mechanical properties (including fracture toughness). In addition, it is believed that further experience will substantiate that certain statements in Specification MIL-S-46099A should be modified slightly when referring to heat-treated composite dual-hardness steel armor. Moreover, further work is required to better determine and understand why certain ballistic results are obtained with composite steel armor.

Therefore, it is recommended that the research effort be continued (as an extension to the contract work just completed) to

*Finish-rolled "cold" to impart texturing.

complete the aforementioned caliber 0.50 studies, to investigate other promising approaches that may develop, and to extend the composite-steel-armor approach to thicker and thinner plates.

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APPENDIX

APPENDIX (U)

Fabricability of Heat-Treatable Dual-Hardness Steel Armor (U)

Although fabrication studies on composite steel armor were not a requirement of the present contract, welding and forming studies were undertaken by U. S. Steel, and similar studies and machinability studies were conducted by other companies and agencies, concurrent with the studies to develop improved heat-treatable dual-hardness steel armor.

Figure A-1A illustrates that composite steel armor is formable before hardening. As-rolled and ground 0.3-inch-thick production plate samples of Composite 9-10 were normalized and tempered to a hardness of about 27 Rockwell C, then formed on a 3-point guided bend-test fixture to bend radii ranging from 1-1/2 inches to 1/2 inch without cracking on the outer fibers—the high-carbon steel is on the tension surface. Both longitudinally and transversely oriented plate samples could be cold-formed 180° to the 1/2-inch radius. The same excellent formability was observed in 0.4-inch plate samples that did not have the surface scale ground off, Figure A-2A. Note that the specimen had been saw-cut. Thicker dual-hardness steel plate composites have been successfully cold-formed by other companies. Figure A-1B illustrates two dished heads, a bracket, a corrugated Z shape, and a U bend cold-formed on production equipment; each piece was formed from normalized and tempered 0.3-inch-thick production plates of composite steel armor (Composite 9-10) with a hardness of about 27 Rockwell C. Later production lots of composite steel armor have been softened to hardnesses of 20 Rockwell C and lower, thus making the composite steel armor even more cold-formable.

A 15-inch-diameter dished head was explosively expanded from an 0.3-inch-thick plate composite with an initial hardness of 27 Rockwell C. The steel exhibited a plastic strain of almost 10 percent before failure occurred after the dome was dished to a depth of about 5-1/2 inches. The fracture was of the shear mode, and no delamination occurred at the bondline.

Figure A-2B illustrates an actuater cylinder fabricated from Composite 9-10 as two half cylinders and joined by full-penetration electron-beam welding. Two projectile impacts are visible in the photograph. The cylinder exhibited the required ballistic protection, and the rear-face bulging after ballistic testing with caliber 0.30 armor-piercing projectiles was slight enough to permit the piston to function. Extruded seamless tubes of dual-hardness steel armor have also been successfully made by another company.

Figure A-3 shows an experimental helicopter seat fabricated from a dished heat (bottom section) and a roll-formed plate (top section). The seat was welded (with covered electrodes and preheat) with a hardenable ferritic weld metal on the front half and an austenitic weld metal on the rear half,* heat-treated,** and ballistically tested by AMRA with caliber 0.30 AP M2 projectiles (24 impacts). The seat itself exhibited a merit rating of about 1.43, whereas the full-penetration double-VEE covered-electrode weld exhibited a merit rating of 1.41.

Figures A-4 and A-5 illustrate two views of a prototype helicopter seat made from heat-treatable composite steel armor. By rounding corners and curving plates, a weight savings of 15 percent was realized over a comparable helicopter seat made originally from ausformed dual-hardness steel armor.

Heat-treated (hardened) dual-hardness steel can be welded by any of the low-hydrogen processes and techniques appropriate to the compositions involved. However, the usual high preheats cannot be employed if the weldment is to be used as-welded because of the low tempering temperature (about 275 F) of the base plate. To minimize heat-affected-zone cracking, austenitic steel electrodes are recommended. Table A lists typical properties of U. S. Steel's dual-hardness composite steel armor.

The fabrication advantages of heat-treated composite armor over ausformed composite armor are that heat-treatable composite armor can be formed hot or cold (in the softened condition), welded in any manner (with or without preheat and postheat, and with partial- or full-penetration welds), readily cut to size with conventional cutting equipment (either hot or cold), drilled or punched, then quenched and tempered to the final desired hardnesses (if the size of welded assemblies permits such heat-treatment privileges). Not only can heat-treatable composite steel armor be cold-formed in the softened condition, but after heat treating, the ductility that may have been exhausted by cold forming is restored, the heat-affected zone resulting from welding is eliminated, and, if the weld metal is heat-treatable, it is hardened.

---

*Other types of welding (for example, MIG short-arc and TIG) have also been successfully used to join dual-hardness composite steel armor.

**There was a slight tendency for contraction to occur during the oil-quenching operation.

Flat, heat-treated composite steel armor can also be produced, and it can be produced in large plate widths and heavy thicknesses if desired. Although some of the fabrication advantages are lost with the use of large flat plates, subassemblies of welded flat plates would still derive the benefits of heat treating after welding. Last, but not least, major cost savings can be realized from the use of heat-treatable composite steel armor.

Table A

Interim Typical Properties of USS Dual-Hardness Composite Steel Armor

Chemical Composition, Percent

	C	Mn	P	S	Si	Ni	Cr	Mo
Front	0.55	0.75	0.008	0.008	0.25	1.20	0.75	0.50
Rear	0.30	0.75	0.008	0.008	0.25	1.20	0.75	0.50

Heat Treatment

Hardening (Quenching and Tempering)

Optimum hardness for resistance to penetration by armor-piercing projectiles is obtained by austenitizing at 1500 F, cooling at an H value of about 0.3 to eliminate quench cracking, and tempering at 250 to 300 F.

Softening (Normalizing and Tempering)

Material may be softened for forming purposes by austenitizing at 1480 F, air cooling, tempering at about 1290 F for 2 hours, and air cooling.

Mechanical Properties

Yield Strength (0.2% Offset) ksi	Tensile Strength, ksi	Elongation, %	Reduction of Area, %	Charpy V-Notch Energy Absorption, ft-lb
Quenched and Tempered 0.5-Inch-Thick Plate				
210	285	3.5	11.0	6
Normalized and Tempered 0.32-Inch-Thick Plate				
92	110	14.0	33.1	--

Fabricability

Weldability

Can be welded by any of the low-hydrogen processes and techniques appropriate to the compositions involved. However, the usual high preheats cannot be employed if the weldment is to be used as-welded because of the low tempering temperature (250 to 300 F) of the base plate.

(Continued)

Table A (Continued)

Interim Typical Properties of USS Dual-Hardness Composite Steel Armor

Fabricability (Continued)

Weldability (Continued)

If the weldment is heat treated after welding, preheat temperature need not be restricted. To minimize heat-affected-zone cracking, austenitic electrodes are recommended. For heat-treated weldments, a heat-treatable electrode such as Hardex 52 is recommended for the front face.

Formability

After normalizing and tempering to a front-face hardness of about R_C 20, plate can be cold-formed to a radius of 2t in thicknesses of 1/4 to 1/2 inch. Hot forming can be readily accomplished in the temperature range 1500 to 2000 F, but should be followed by quenching and tempering.

Machinability

In the normalized and tempered (20 R_C) condition, the dual-hardness steel has been readily ground, milled, sheared, drilled, tapped, and bent, with workability comparing approximately to that of regular annealed tool steel.

Ballistic Properties

The average obtainable merit rating for hardened plates is 1.4.

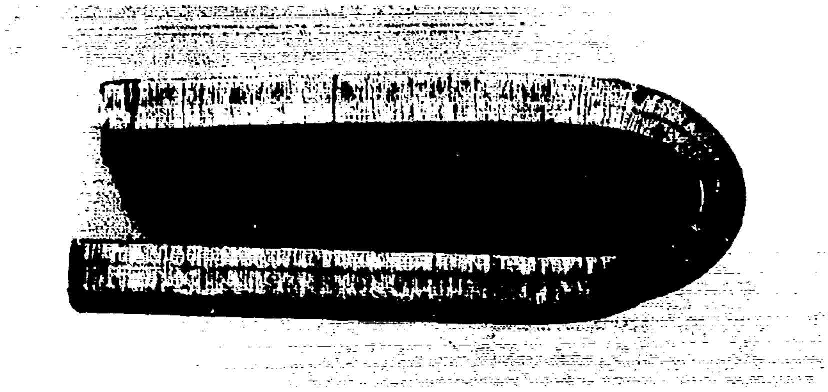
A. Guided bend-test specimens bent to radii ranging from 1-1/2 to 1/2 inch. X1/3.

B. Various cold-formed parts. X1/6.

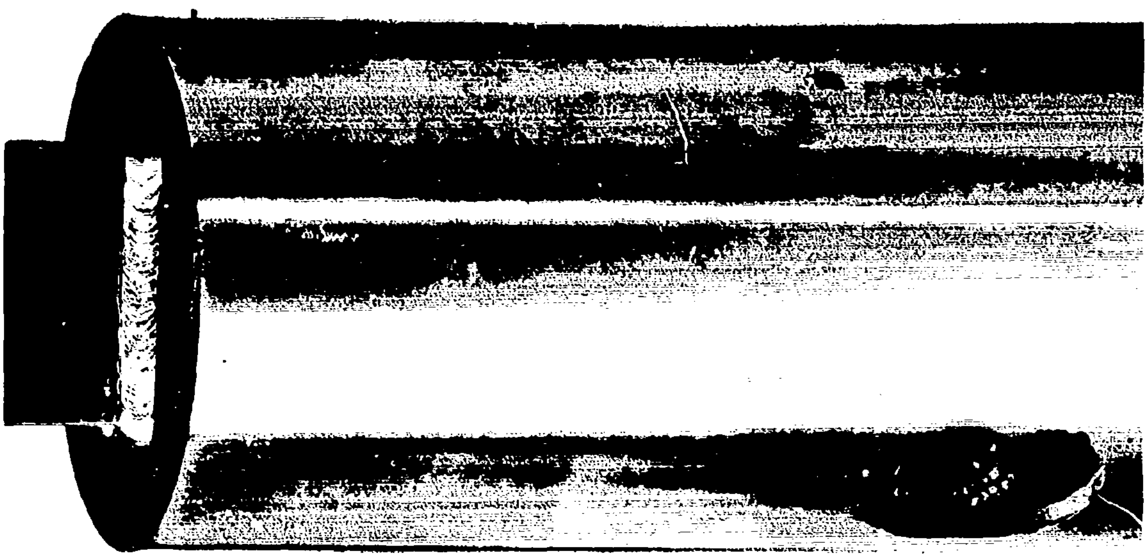
Figure A-1. Results of formability studies on normalized and tempered 0.3-inch-thick plates of Composite 9-10.

P-6435A-2
P-6563A-1

Figure A-1A, B



A. Plate sample (0.4-inch thick) cold-formed 180° to a 1/2-inch radius. Composite 20-21. X1.



B. Formed, welded, heat-treated, and ballistically tested actuator cylinder. Composite 9-10. X1.

Figure A-2. Illustrations of the fabricability of normalized and tempered dual-hardness steel armor.

Commercial Photograph
P-7254A-1

Figure A-2 A,B

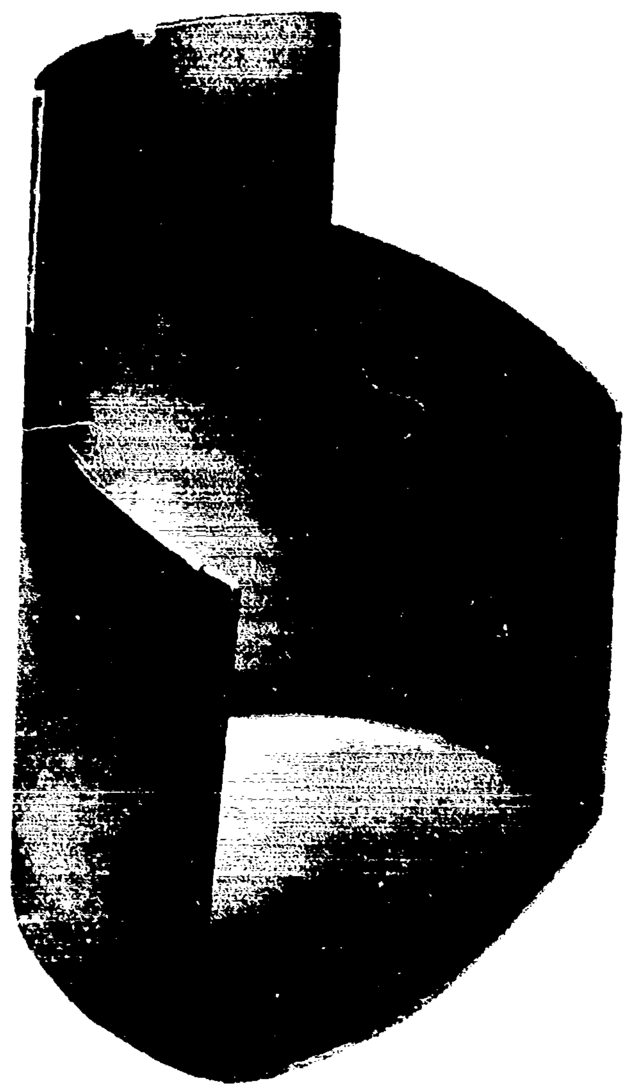


Figure A-3. Experimental helicopter seat of dual-hardness steel armor cold-formed (in two sections) then welded and heat-treated. Material was 0.305-inch-thick plate of Composite 9-10. X1/6.

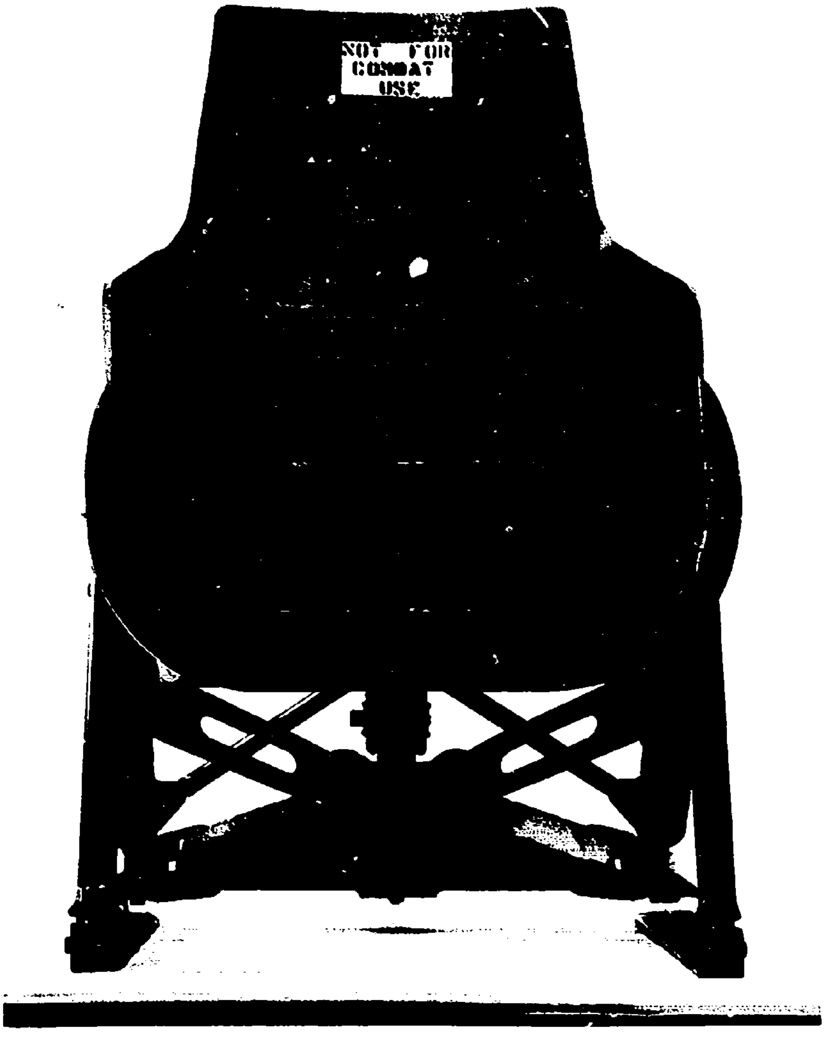


Figure A-4. Prototype helicopter seat of dual-hardness steel (front view) that was cold-formed, welded, then heat-treated. Material was 0.305-inch-thick plate of Composite 9-10. X1/6.

Commercial Photograph

Figure A-4

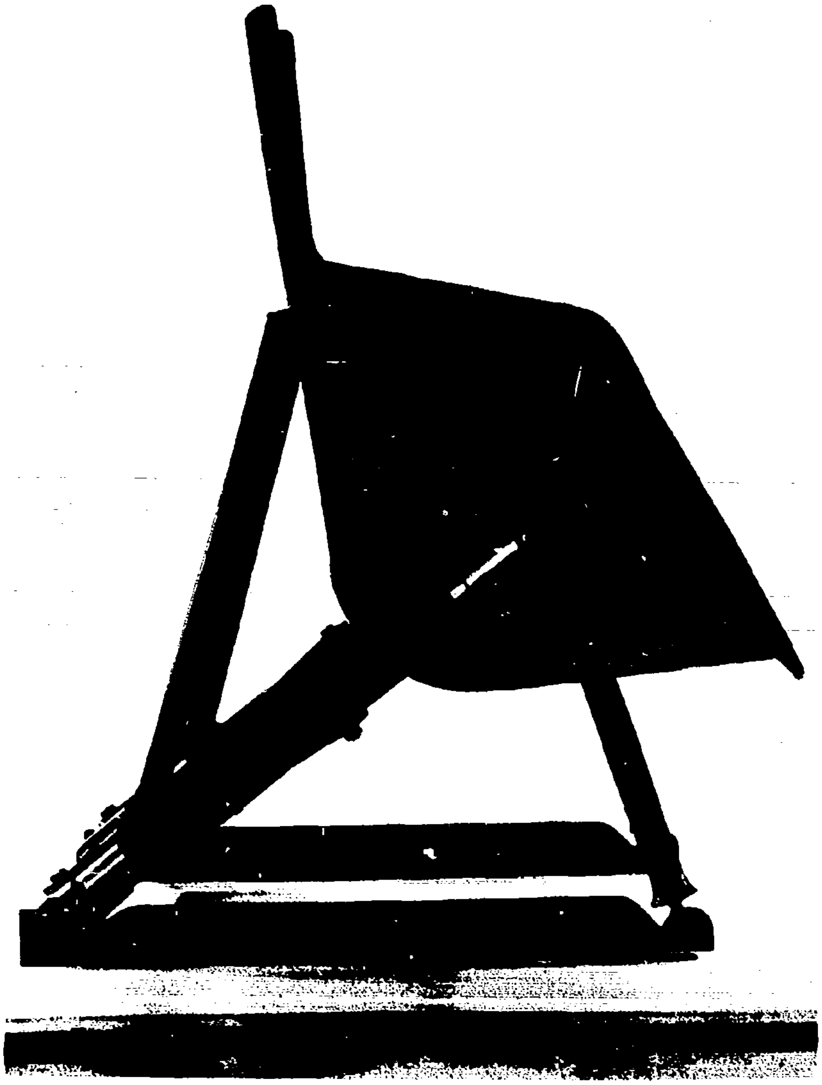


Figure A-5. Prototype helicopter seat shown in Figure A-4 (side view). X1/6.

Commercial Photograph

Figure A-5

Table I

Compositions of Steels for Evaluation—Percent+
(Check Analyses)

Steel	Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	V	Al++	N	Co
						Laboratory Steels							
1	T5890	0.25	0.79	0.004	0.005	0.21	1.02	0.54	0.54	--	0.031	0.010	--
2	T5889	0.28	0.74	0.004	0.004	0.19	1.02	0.50	0.54	--	0.031	0.010	--
3	T5892	0.31	0.81	0.003	0.004	0.25	1.01	0.49	0.54	--	0.037	0.008	--
4	T5893	0.52	0.75	0.003	0.002	0.23	0.02	0.51	0.54	--	0.027	0.009	--
5	T5894	0.53	0.76	0.003	0.002	0.24	0.02	0.47	0.54	--	0.030	0.008	--
6	T5895	0.57	0.77	0.005	0.003	0.26	1.01	0.49	0.54	--	0.030	0.009	--
7	T5896	0.61	0.76	0.004	0.003	0.27	0.02	0.51	0.54	--	0.025	0.009	--
8	T5897	0.53	0.76	0.010	0.012	0.25	0.02	0.51	0.55	--	0.031	0.008	--
						Production Steels							
9	1P0612	0.54	0.61	0.007	0.012	0.24	1.44	0.64	0.52	--	0.051	0.008	--
10	1P0611	0.32	0.32	0.004	0.010	0.24	2.98	1.48	0.45	--	0.056	0.010	--
11	X51289	0.13	0.29	0.009	0.011	0.25	2.97	1.60	0.51	--	0.058	0.012	--
12	1P0392+++	0.32	0.28	0.008	0.009	0.24	3.05	0.98	0.29	--	0.033	ND	--
13	50400	0.10	0.83	0.005	0.004	0.34	4.88	0.55	0.53	0.06	0.019	0.002	--
14	5P0719	0.10	0.35	0.007	0.004	0.23	5.33	0.49	0.57	0.06	0.020	0.012	--
15	3961329	0.23	0.15	0.002	0.010	<0.02	8.44	0.42	0.50	0.04	0.005	0.003	4.03
16	L50250*	0.004	<0.02	0.003	0.006	0.024	12.30	5.11	2.97	--	0.19	0.010	--
17	L50446**	0.003	<0.02	0.003	0.007	0.005	17.90	--	2.96	--	0.008	0.004	7.73
18	L50447***	0.003	<0.02	0.001	0.004	0.003	17.00	--	4.65	--	0.052	0.003	7.60
19	75B522+++	0.34	0.87	0.015	0.015	0.34	0.60	0.58	0.21	--	0.012	ND	--
20	1P1307	0.51	0.62	0.006	0.006	0.28	1.05	0.51	0.48	--	0.029	0.010	--
21	1P1306	0.31	0.77	0.008	0.008	0.32	1.03	0.50	0.47	--	0.025	0.010	--
22	1P1575	0.54	0.80	0.009	0.004	0.26	1.19	0.74	0.48	--	0.020	0.010	--
23	1P1576	0.29	0.80	0.008	0.004	0.25	1.22	0.74	0.48	--	0.017	0.010	--

+All the steels listed were available in plates 3/4 to 3 inches in thickness and thus could be conveniently used as components of composites prior to bonding.

++Total.

+++Ladle analysis.

*Steel also contained 0.21 percent titanium.

**Steel also contained 0.20 percent titanium.

***Steel also contained 0.50 percent titanium.

NOTE: ND means not determined.

Table II

Compositions of Experimental Armor Steels Made at the Laboratory—Percent

Steel	Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	V	Cb	Al*	N
A+	V9213	0.34	0.72	<0.001	0.005	0.22	1.00	0.52	0.52	--	--	0.022	0.008
B+	V9214	0.36	0.74	<0.001	0.005	0.22	1.00	0.51	0.51	--	--	0.020	0.008
C+	V9215	0.40	0.72	<0.001	0.005	0.21	0.98	0.51	0.52	--	--	0.020	0.008
D+	V9216	0.41	0.74	<0.001	0.004	0.23	1.00	0.52	0.51	--	--	0.020	0.008
E+	V9217	0.44	0.72	<0.001	0.004	0.20	0.98	0.51	0.52	--	--	0.023	0.010
F	W8484	1.00	0.28	0.006	0.004	0.23	0.02	0.59	--	--	--	0.026	0.005
G+	W8485	0.96	0.36	0.006	0.004	0.23	0.02	1.44	--	--	--	0.026	0.003
H	W8486	0.50	0.66	0.008	0.005	0.29	0.56	1.02	0.99	--	--	0.032	0.007
I	W8487	0.50	0.64	0.007	0.004	0.27	0.55	1.02	0.54	--	--	0.028	0.008
J+	W8488	0.49	0.76	0.010	0.005	0.29	1.00	0.58	0.55	--	--	0.037	0.007
K	W8489	0.50	0.36	0.005	0.002	0.23	0.49	0.76	0.24	0.07	--	0.007	0.007
L	W8490	0.42	0.37	0.007	0.006	0.27	0.02	1.56	--	0.13	--	0.004	0.004
M+	W8499	0.43	0.36	0.006	0.005	0.27	0.02	1.54	--	0.13	--	0.004	0.032
N+	W8500	0.33	0.78	0.009	0.005	0.30	1.02	0.56	0.56	--	--	0.035	0.006
O+	W8784-2	0.60	0.82	0.001	0.002	0.07	1.24	0.73	0.49	--	--	0.072	0.001
P+	W8785	0.33	0.84	0.001	0.003	0.06	1.22	0.74	0.47	--	--	0.021	0.002
Q	Y9120	0.53	0.65	0.008	0.004	0.28	0.52	1.03	1.00	--	--	0.031	0.001
R	Y9121	0.30	0.46	0.006	0.004	0.27	3.05	1.02	0.28	--	--	0.029	0.001
S	Y9149	0.58	0.89	0.006	0.006	1.49	0.98	0.75	0.50	0.10	0.04	0.004	0.007
T	Y9150	0.31	0.86	0.006	0.006	1.43	0.96	0.72	0.49	0.10	0.05	0.005	0.005
U	Y9151	0.57	1.29	0.004	0.007	1.58	0.02	1.50	0.50	0.10	0.05	0.006	0.008
V	Y9152	0.31	1.24	0.004	0.006	1.50	0.02	1.50	0.49	0.10	0.05	0.006	0.006
J3+	W8488-3	0.45	0.76	0.009	0.018	0.29	1.00	0.53	0.56	--	--	0.037	0.007
N3+	W8500-3	0.30	0.74	0.007	0.022	0.29	1.06	0.56	0.57	--	--	0.033	0.007

+Check carbon analyses. All other analyses represent ingot analyses.
*Acid soluble.

Table III UNCLASSIFIED

Calculated Transformation Temperatures of Experimental Armor Steels

Steel	Temperature, F Ae3*	Ae1**	Ms***
1	1473	1317	681
2	1461	1317	668
3	1453	1318	645
4	1404	1343	545
5	1400	1343	542
6	1355	1319	480
7	1373	1345	486
8	1401	1344	538
9	1355	1318	485
10	1393	1319	539
11	1489	1326	654
12	1390	1298	581
13	1442	1222	640
14	1434	1215	660
15	1248	1128	599
19	1455	1334	646
20	1381	1323	528
21	1457	1321	650
22	1359	1323	475
23	1452	1322	636
A	1440	1320	632
B	1430	1318	617
C	1416	1319	594
D	1411	1319	585
E	1400	1319	568
F	+	1359	288
G	+	1392	223
H	1406	1356	488
I	1398	1357	513
J	1383	1324	518
K	1400	1352	568
L	1444	1400	591
M	1436	1399	580
N	1444	1322	621
O	1319	1314	434
P	1420	1314	608
Q	1396	1358	470
R	1395	1296	580
S	1446	1376	449
T	1545	1374	629
U	1475	1426	408
V	1570	1425	581

(Continued)

UNCLASSIFIED

Table III

Calculated Transformation Temperatures of Experimental Armor Steels

	Temperature, F		
Steel	Ae_3*	Ae_1**	M_s***

*$Ae_3(F) = 1600 - 375 \times \%C - \left[(25 \times \%Mn) - 4.5\right] + \left[(80 \times \%Si) - 10\right] - 32 \times \%Ni - 3 \times \%Cr$ + Mo factor (for various carbon contents).

Source: Climax Molybdenum Company.[4)]

**$Ae_1(F) = 1333 - 25 \times \%Mn + 40 \times \%Si - 26 \times \%Ni + 42 \times \%Cr$.

Source: Lambert and Grange.[5)]

***$M_s(F) = 1000 - 650 \times \%C - 70 \times \%Mn - 35 \times \%Ni - 70 \times \%Cr - 50 \times \%Mo + 27 \times \%Co$.

Source: Grange and Stewart;[6)] Cobalt factor was obtained from Holloman and Jaffe.[7)]

+A_{cm} temperature was not calculated.

Table IV

Hardnesses and Quench Cracks Developed in Gradient-Furnace Specimens* of Carbon Series

Steel	Carbon Content, %	Quenching Medium	Rockwell C Hardness at Distance Corresponding to Indicated Quenching (Austenitizing) Temperature 1725 F	1680 F	1595 F	1545 F	1495 F	1425 F	1385 F	1280 F
N	0.33	Water	54.0	54.0	54.5	54.0	54.0	52.5	25.0	16.5
		Oil	52.0	52.0	51.5	51.5	51.5	50.5	38.0	13.0
A	0.34	Water	55.5	55.5	55.5	55.0	55.0	54.5	50.0	20.5
		Oil	52.0	52.0	52.0	52.0	52.0	52.0	44.5	20.0
B	0.36	Water	57.0	57.0	57.0	57.0	57.0	57.0	54.5	21.0
		Oil	54.0	54.0	54.0	54.0	54.0	54.0	50.0	20.5
C	0.40	Water	59.5	59.5	59.5	59.0	59.0	59.0	57.0	22.0
		Oil	56.5	56.5	56.0	56.0	55.5	55.5	53.0	22.0
D	0.41	Water	60.5	60.5	60.5	60.5	60.5	60.0	58.0	24.0
		Oil	58.5	58.0	58.0	58.0	58.0	57.5	52.5	22.5
E	0.44	Water	61.5	61.5	61.5	61.5	61.0	61.0	59.0	24.0
		Oil	59.0	59.0	59.0	59.0	59.0	58.5	55.5	23.5
J	0.49	Water	63.0	62.0	62.0	62.0	62.0	61.5	25.0	23.0
		Oil	61.5	61.5	61.5	61.5	61.5	60.5	50.0	20.5

NOTE: Quench cracks were observed in the water-quenched specimen of Steel J at locations corresponding to austenitizing temperatures of 1410 F and higher, in the water-quenched specimen of Steel E at locations corresponding to austenitizing temperatures of 1595 F and higher, and in the water-quenched specimen of Steel D at locations corresponding to austenitizing temperatures of 1680 F and higher.

*7-inch-long by 3/4-inch-wide by 1/2-inch-thick specimens.

Table V

Amount of Retained Austenite in Gradient-Furnace Specimens at Location Corresponding to an Austenitizing Temperature of 1500 F

Steel	Carbon Content, %	Quenching Medium	Retained Austenite, %*
N	0.33	Water	<2
		Oil	4
A	0.34	Water	2
		Oil	4
B	0.36	Water	<2
		Oil	5
C	0.40	Water	3
		Oil	6
D	0.41	Water	5
		Oil	7
E	0.44	Water	5
		Oil	6
J	0.49	Water	5
		Oil	8

*As determined by X-ray diffraction analysis.

Table VI

Retained Austenite Percentages in Front Face of Dual-Hardness Steel Ballistic-Test Plates

Composite	Front-Face Carbon, %	Austenitizing Temp, F	Quenching Medium	Retained Austenite, %*: Abrasively Polished on Billiard Cloth	Retained Austenite, %*: Electro-chemically Polished
J3-N3	0.45	1500	Water	6.0	5.0
			Oil	6.5	6.5
J-N	0.49	1525	Water	6.5	7.0
			Oil	7.0	7.5
K-L-N	0.50	1525	Water	4.5	5.0
			Oil	7.0	7.0
G-K-L-N	0.96	1475	Water	10.5	9.5
		1600	Oil	21.0	23.0

*Determined by X-ray diffraction analysis.

Table VII

Heat Treatments and As-Quenched Hardnesses of Experimental Armor Steels

Steel	Heat No.	Carbon, %	Suggested Aust. Temp., F*	Suggested Quenching Medium*	As-Quenched Hardness, R_C	
					Oil*	Water*
A	V9213	0.34	1495-1545	Oil or Water	52.0	55.0
B	V9214	0.36	1495-1545	Oil or Water	54.0	57.0
C	V9215	0.40	1495-1545	Oil or Water	56.0	59.0
D	V9216	0.41	1495-1545	Oil or Water	58.0	60.5
E	V9217	0.44	1495-1545	Oil or Water	59.0	61.5
F	W8484	1.00	1470-1520	Water	--	65.5
G	W8485	0.96	(1450-1500	Water)	--	66.5
			(1600-1650	Oil)	63.5	--
H	W8486	0.50	1500-1550	Oil	60.0	61.0
I	W8487	0.50	1550-1600	Oil	59.5	61.5
J	W8488	0.49	1490-1540	Oil	61.5	62.0
K	W8489	0.50	1500-1550	Oil	58.5	61.0
L	W8490	0.42	1550-1600	Oil or Water	54.5	58.0
M	W8499	0.43	1515-1565	Oil or Water	55.5	59.0
N	W8500	0.33	1490-1540	Oil or Water	51.5	54.0
O	W8784-2	0.60	1500-1550	Oil	61.0	--
P	W8785	0.33	1500-1550	Oil or Water	49.0	--
Q	Y9120	0.53	1500-1550	Oil	62.0	--
R	Y9121	0.30	1500-1550	Oil or Water	53.0	--
S	Y9149	0.58	1600-1700	Oil	62.0	--
T	Y9150	0.31	1600-1700	Oil or Water	52.0	--
U	Y9151	0.57	1600-1700	Oil	61.0	--
V	Y9152	0.31	1600-1700	Oil or Water	51.0	--

*As determined from gradient-furnace studies (except for Steels O through V).

Table VIII

Effect of Front-Plate/Rear-Plate Thickness Proportions on Ballistic Properties (U)

Code	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks

Table VIII-A

Composite 9-10 Tested With Caliber 0.30 AP M2 Projectiles at 0^{o} Obliquity*

Code	Thickness, inch	Areal Density, lb/ft^2	Front	Rear	Front	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
11	0.301	12.1	0	100	--	52.0	2130 (3 + 3)**	1.17	--
1	0.302	12.1	10	90	59.0	51.5	2370 (3 + 3)	1.32	--
2	0.300	12.1	20	80	61.0	51.0	2420 (2 + 2)	1.35	Some face cracking.
3	0.296	11.9	30	70	60.0	52.0	2460 (2 + 2)	1.37	Some face cracking.
4	0.295	11.9	40	60	60.0	52.5	2635 (2 + 2)	1.47	Fractured after five rounds.
5	0.302	12.1	55	45	60.0	51.5	2620 (1 + 1)	1.45	Fractured after four rounds,
6	0.302	12.1	60	40	60.0	51.0	2675 (2 + 2)	1.48	Fractured after six rounds.
7	0.302	12.1	75	25	60.5	52.0	2560 (2 + 2)	1.42	Fractured after four rounds.
8	0.302	12.1	90	10	60.0	53.0	2455 (1 + 1)	1.36	Fractured after two rounds.
9	0.302	12.1	95	5	60.5	52.0	2450 (1 LC)	--	Fractured after one round.
10	0.296	11.9	100	0	59.5	--	2495 (1 + 1 HP)	>1.39	Fractured after three rounds.

(Continued)

Table VIII (Continued)

Effect of Front-Plate/Rear-Plate Thickness Proportions on Ballistic Properties (U)

Code	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
Table VIII-B									
Composite 9-10 Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity*									
12	0.504	20.4	35	65	59.0	51.0	2305 (1 + 1)	1.28	Fractured after four rounds.
13	0.505	20.4	45	55	59.0	52.0	2340 (2 + 2)	1.27	Fractured after four rounds.
14	0.502	20.3	60	40	59.0	51.0	2295 (1 + 1)	1.27	Fractured after three rounds.
Table VIII-C									
Composite 22-21 Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity***									
5-6-6	0 634	25.7	0	100	54.0	51.0	2370 (2 + 2)	1.15	Some rear spalling.
5-6-5	0.636	25.8	5	95	60.0	51.0	2435 (2 + 2)	1.18	Some rear cracking and spalling.
5-6-4	0.639	25.9	15	85	61.0	50.0	2529 (2 + 2)	1.22	Some rear cracking.
5-6-1	0.641	26.0	20	80	61.0	50.5	2629 (2 + 2)	1.27	Some rear cracking.
5-6-2	0.640	26.0	30	70	61.5	51.5	2637 (2 + 2)	1.27	Slight front and rear cracking.
5-6-3	0.643	26.1	35	65	62.0	51.0	2601 (1 + 1)	1.25	Some front and rear cracking.

(Continued)

Table VIII (Continued)

Effect of Front-Plate/Rear-Plate Thickness Proportions on Ballistic Properties (U)

Table VIII-C (Continued)

Composite 22-21 Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity***

Code	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
5-6-3	0.639	25.9	50	50	60.5	51.0	2601 (1 + 1)	1.26	Bad front cracking. Some rear cracking.
5-6-2	0.637	25.8	60	40	60.0	51.0	2619 (1 + 1)	1.27	Fractured after five rounds.
5-6-1	0.639	25.9	70	30	60.5	50.0	2297 (1 + 1)	1.11	Fractured after four rounds.
5-6-4	0.678	27.4	30	70	61.0	50.5	2737 (2 + 2)	1.28	Some front and rear cracking.

*Plate samples were austenitized at 1500 F, oil-quenched, tempered at 250 F, and water-quenched.

**Number of partials and completes in the average.

***Plate samples were austenitized at 1500 F, spray-quenched with a glycol-water solution, tempered at 275 F, and water-quenched.

Table IX

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C** Front	Plate Hardness, R_C** Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
Table IX-A											
Laboratory Roll-Bonded 2-Layer Plate Composites											
39C	7-13	1500 F Oil 300 F	0.265	10.7	30	70	60.0	37.5	2506 (2 + 2)***	1.49	Slight front cracking.
15C	J3-N3 (Open-hearth quality)	1500 F Oil 250 F (2)	0.315	12.7	45	55	59.0	49.5	2541 (3 + 3)	1.35	
17C	J3-N3 (Open-hearth quality)	1500 F Oil 250 F (2)	0.318	12.8	50	50	58.0	46.0	2526 (1 + 1)	1.33	Slight front cracking.
19C	J-N	1500 F Water 250 F (2)	0.315	12.7	45	55	60.0	51.5	2633 (2 + 2)	1.40	Some front plate cracking (even before testing).
13C	H-15	1500 F Oil 250 F (2)	0.290	11.7	60	40	57.5	51.5	2489 (2 + 2)	1.39	
29C	G-11	1600 F Oil 300 F	0.295	12.0	40	60	65.0	43.0	2566 (2 + 2)	1.41	
31C	G-11	1600 F Oil 400 F	0.283	11.5	30	70	61.0	43.0	2418 (2 + 2)	1.37	
25C	F-A	1475 F Water 400 F	0.320	13.0	30	70	63.0	46.0	2550 (1 + 1)	1.33	Plate delaminated at bondline.

(Continued)

Table IX (Continued)

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Table IX-A (Continued)

Laboratory Roll-Bonded 2-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C** Front	Plate Hardness, R_C** Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
1-1	E-2	1500 F Oil 250 F	0.283	11.5	50	50	58.5	47.0	2695 (AMRA)	1.56	
3	E-2	1500 F Water 250 F	0.293	11.9	50	50	58.0	50.5	2445 (AMRA)	1.38	
5	E-A	1500 F Oil 250 F	0.299	12.2	50	50	57.0	50.5	2580 (AMRA)	1.43	
7	E-A	1500 F Water 250 F	0 295	12.1	55	45	59.0	52.5	2440 (AMRA)	1.37	
5892	D-3	1600 F Water 250 F	0.281	11.4	50	50	58.0	53.0	2440 (AMRA)	1.41	
84-85	O-P (Ultraservice quality)	1500 F Oil 300 F	0.320	13.0	50	50	60.0	48.0	2478 (1 + 1)	1.29	Bad front spalling.

Table IX (Continued)

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Table IX-B

Laboratory Roll-Bonded 3-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Middle	Rear	Plate Hardness, R_C** Front	Middle	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
21C	K-L-N	1525 F Oil 250 F (2)	0.312	12.6	20	45	35	58.0	54.5	49.0	2411 (2 + 2)	1.29	
23C	K-L-N	1525 F Water 250 F (2)	0.310	12.5	20	45	35	59.0	57.5	51.5	2614 (3 + 3)	1.40	Some front and rear cracking.
33C	G-L-12	1600 F Oil 350 F	0.306	12.3	30	35	35	62.0	52.5	47.5	2518 (2 + 2)	1.36	Slight cracking.
41C	6-E-13	1500 F Oil 300 F	0.315	12.7	30	40	30	57.5	56.0	40.5	2508 (2 + 2)	1.33	
43C	6-E-13	1500 F Water 300 F	0.308	12.4	25	50	25	59.0	58.5	38.0	2483 (1 + 1)	1.34	Some front and rear cracking.
35C	G-C-N	1600 F Oil 300 F	0.310	12.5	20	40	40	65.0	54.5	52.5	2536 (2 + 2)	1.36	Slight front cracking.
37C	G-C-N	1600 F Oil 400 F	0.312	12.6	20	40	40	62.0	53.5	49.5	2461 (1 + 1)	1.31	
27C	F-C-1	1475 F Water 400 F	0.310	12.5	25	50	25	$\frac{30.0}{62.0}$	55.0	46.5	2073 (1 + 1)	1.11	Erratic front plate hardnesses (too soft).
11C	J-L-N	1525 F Water 250 F (2)	0.315	12.7	40	35	25	60.5	57.5	52.0	2525 (2 + 2)	1.34	Surface cracks progressed through plate.

(Continued)

Table IX (Continued)

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Table IX-B (Continued)

Laboratory Roll-Bonded 3-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	Middle	Rear	Plate Hardness, R_C** Front	Middle	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
9C	J-L-N	1525 F Oil 250 F (2)	0.317	12.8	30	40	30	58.5	54.5	47.0	2486 (3 + 3)	1.31	
5C	K-12-11	1525 F Oil 250 F (2)	0.307	12.4	30	40	30	56.0	53.5	37.0	2436 (2 + 2)	1.31	
7C	K-12-11	1525 F Water 250 F (2)	0.303	12.2	40	30	30	58.0	55.5	43.0	2381 (1 + 1)	1.30	Slight separation at bondline.
1C	H-D-13	1500 F Oil 250 F (2)	0.307	12.4	20	50	30	57.0	56.5	38.0	2334 (1 + 1)	1.26	
3C	H-D-13	1500 F Water 250 F (2)	0.310	12.5	20	40	40	60.0	58.5	40.0	2541 (2 + 2)	1.36	
9	9-10-13 (Roll- and diffusion-bonded)	1500 F Oil 250 F	0.283	11.6	18	32	50	59.0	51.5	41.0	2415 (AMRA)	1.39	

Table IX (Continued)

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	2	3	Rear	Plate Hardness, R_C** Front	2	3	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
Table IX-C															
Laboratory Roll-Bonded 4-Layer Plate Composites															
48C	G-K-L-N	1475 F Water 350 F	0.320	12.9	15	30	30	25	63.0	57.5	53.5	53.0	2598 (1 + 1)	1.36	Some front and rear cracking.
46C	G-K-L-N	1600 F Oil 350 F	0.305	12.3	10	35	35	20	65.0	55.5	52.5	51.0	2565 (1 + 1)	1.39	
50C	G-J-B-13	1600 F Oil 350 F	0.325	13.2	15	25	30	30	65.0	55.0	52.0	40.0	2571 (3 + 3)	1.33	Slight front cracking.
Table IX-D															
Roll-Bonded Versus Roll- and Diffusion-Bonded 2-Layer Production Plate Composites															
17	9-10 (Roll-bonded)	1500 F Oil 250 F (2)	0.299	12.1	50			50	62.0			53.0	2670 (AMRA)	1.48	Face spalling after eight rounds.
16	9-10 (Roll- and diffusion-bonded)	1500 F Oil 250 F (2)	0.300	12.1	65			35	62.0			52.5	2540 (AMRA)	1.42	Some face cracking.

Table IX (Continued)

Ballistic Test Results on Composites Tested With Caliber 0.30 AP M2 Projectiles at 0^{o} Obliquity (U)

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_{C}** Front	Plate Hardness, R_{C}** Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
				Table IX-E							
				Explosively Clad Plate Composites							
2B	J-N(XA) (Explosively clad)	1500 F Oil 250 F (2)	0.302	12.2	50	50	59.5	50.5	2386 (AMRA)	1.30	Some cracking.
3B	J-N(XB) (Explosively clad)	1500 F Oil 250 F (2)	0.302	12.2	50	50	59.0	51.0	2498 (AMRA)	1.38	Some face cracking.
52C	J-N(XD) (Explosively clad and rolled)	1500 F Oil 250 F (2)	0.317	12.8	50	50	61.0	51.0	2624 (3 + 3)	1.39	
54C	J-N(XF) (Explosively clad and rolled)	1500 F Oil 250 F (2)	0.320	12.9	50	50	61.0	53.0	2557 (2 + 2)	1.34	
				Table IX-F							
				Weld-Overlayed and Rolled Plate Composites							
4B	Weld Overlay A (Hardex 45 on N)	1500 F Oil 250 F (2)	0.324	13.1	40	60	59.0	50.5	2664 (AMRA)	1.40	Slight face cracking.
5B	Weld Overlay B (Hardex 52 on N)	1500 F Oil 250 F (2)	0.323	13.1	35	65	60.0	51.0	2750 (AMRA)	1.4	Some face cracking.

*First line = austenitizing temperature; second line = quenching medium; third line = tempering temperature.

**The hardnesses of the intermediate layers of the tricomposites and quadcomposites were estimated from other heat-treating studies.

***Number of partials and completes in the average.

Table X

Ballistic Test Results of Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Table X-A

Laboratory Roll-Bonded 2-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness, Proportions, % Front	Layer Thickness, Proportions, % Rear	Plate Hardness, R_C** Front	Plate Hardness, R_C** Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
40C	7-13	1500 F Oil 300 F	0.585	23.7	45	55	62.0	41.0	2404 (2 + 2)***	1.23	
14C	H-15	1500 F Oil 250 F (2)	0.543	22.0	40	60	57.5	49.0	2391 (2 + 2)	1.27	Some spalling and cracking.
16C	J3-N3 (Open-hearth quality)	1500 F Oil 250 F (2)	0.578	23.4	40	60	58.0	49.0	2485 (1 + 1)	1.28	Slight front spalling.
18C	J3-N3 (Open-hearth quality)	1500 F Water 250 F (2)	0.577	23.3	50	50	58.5	52.0	2582 (2 + 2)	1.33	Some spalling and cracking.
20C	J3-N3 (Open-hearth quality; finished rolled cold)	1500 F Water 250 F (2)	0.575	23.3	45	55	60.0	52.0	2527 (2 + 2)	1.30	Bad back spalling. Some cracking also.
6B	J-N	1500 F Water 250 F (2)	0.559	22.5	45	55	59.5	51.5	2516 (AMRA)	1.30	Fractured after five rounds.
7B	J-N	1500 F Oil 250 F (2)	0.563	22.6	45	55	59.5	51.5	2440 (AMRA)	1.26	Some face cracking and delamination.
30C	G-11	1600 F Oil 300 F	0.585	23.7	45	55	64.0	42.0	2386 (1 + 1)	1.22	Plate delaminated after two rounds. Bad front cracking also.

(Continued)

Table X (Continued)

Ballistic Test Results of Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Table X-A (Continued)

Laboratory Roll-Bonded 2-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Rear	Plate Hardness, R_C** Front	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
32C	G-11	1600 F Oil 400 F	0.585	23.7	45	55	62.0	43.0	2311 (3 + 3)	1.18	Some delamination, cracking, and spalling.
26C	F-A	1475 F Water 400 F	0.570	23.0	40	60	63.0	51.5	2353 (1 Partial)	1.22	Plate completely delaminated at bond-line after being hit once.
4	E-2	1500 F Water 250 F	0.548	22.4	60	40	60.5	51.5	2385 (AMRA)	1.26	
2	E-2	1500 F Oil 250 F	0.546	22.3	50	50	60.0	50.0	2275 (AMRA)	1.20	
8	E-A	1500 F Water 250 F	0.550	22.2	50	50	61.0	52.0	2400 (AMRA)	1.27	Some face cracking.
6	E-A	1500 F Oil 250 F	0.558	22.8	50	50	58.5	51.5	2270 (AMRA)	1.18	
84-85	O-P (Ultraservice quality)	1525 F Oil 300 F	0.584	23.6	50	50	62.0	50.0	2422 (1 + 1)	1.24	Plate separated at bondline after three rounds.
49-50	S-T	1650 F Glycol-Water 275 F	0.652	26.4	50	50	61.0	53.0	2461 (3 + 3)	1.18	Front and rear cracking. Also rear spalling (large spalls).
51-52	U-V	1650 F Glycol-Water 275 F	0.655	26.5	50	50	62.0	53.0	2319 (1 + 1)	1.11	Front cracking and rear spalling (large spalls).

(Continued)

Table X (Continued)

Ballistic Test Results of Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Table X-B

Laboratory Roll-Bonded 3-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	Middle	Rear	Plate Hardness, R_C** Front	Middle	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
28C	F-C-1	1475 F Water 400 F	0.580	23.5	30	35	35	61.0	55.0	47.0	2493 (2 + 2)	1.28	Some spalling and cracking.
2C	H-D-13	1500 F Oil 250 F (2)	0.572	23.2	35	35	30	58.5	56.5	38.5	2438 (2 + 2)	1.26	Front spalling.
4C	H-D-13	1500 F Water 250 F (2)	0.570	23.0	30	35	35	60.5	58.5	40.0	2382 (2 + 2)	1.24	Bad front cracking.
22C	K-L-N	1525 F Oil 250 F (2)	0.575	23.3	25	35	40	60.0	54.5	51.5	2433 (2 + 2)	1.25	Spalling and cracking.
24C	K-L-N	1525 F Water 250 F (2)	0.570	23.0	20	35	45	60.0	57.5	53.5	2532 (2 + 2)	1.32	Cracking and slight spalling.
6C	K-12-11	1525 F Oil 250 F (2)	0.573	23.2	35	35	30	56.5	53.5	41.5	2479 (2 + 2)	1.28	Some cracking.
8C	K-12-11	1525 F Water 250 F (2)	0.575	23.3	40	30	30	59.5	55.5	42.5	2408 (2 + 2)	1.24	Cracking and spalling.
12C	J-L-N	1525 F Water 250 F (2)	0.580	23.5	40	30	30	62.5	57.5	55.0	2476 (2 + 2)	1.27	Slight face cracking.
10C	J-L-N	1525 F Oil 250 F (2)	0.585	23.7	40	30	30	59.0	54.5	51.5	2364 (1 + 1)	1.21	

(Continued)

Table X (Continued)

Ballistic Test Results of Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Table X-B (Continued)

Laboratory Roll-Bonded 3-Layer Plate Composites

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	Middle	Rear	Plate Hardness, R_C** Front	Middle	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
34C	G-L-12	1600 F Oil 350 F	0.587	23.8	35	35	30	62.0	52.5	51.0	2433 (2 + 2)	1.24	Slight face cracking.
42C	6-E-13	1500 F Oil 300 F	0.583	23.5	30	40	30	60.5	56.0	41.0	2448 (2 + 2)	1.25	Some front cracking.
44C	6-E-13	1500 F Water 300 F	0.580	23.5	30	40	30	60.0	58.5	39.0	2497 (2 + 2)	1.28	Some front cracking and separation at bondline.
36C	G-C-N	1600 F Oil 300 F	0.582	23.6	25	40	35	63.5	54.5	53.5	2370 (3 + 3)	1.21	Slight cracking.
38C	G-C-N	1600 F Oil 400 F	0.583	23.6	30	35	35	63.0	53.5	53.0	2423 (2 + 2)	1.24	Slight edge front spall.
10	9-10-13 (Roll- and diffusion-bonded)	1500 F Oil 250 F	0.526	21.3	18	32	50	59.0	51.5	41.0	2220 (AMRA)	1.20	Some face cracking.

(Continued)

Table X (Continued)

Ballistic Test Results of Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft²	Layer Thickness Proportions, % Front	2	3	Rear	Plate Hardness, R_C** Front	2	3	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
							Table X-C								
							Laboratory Roll-Bonded 4-Layer Plate Composites								
51C	G-J-B-13	1600 F Oil 350 F	0.567	22.9	20	25	25	30	64.0	55.0	52.0	40.0	2337 (2 + 2)	1.22	
45C	E-A-E-2	1500 F Water 250 F (2)	0.542	22.0	25	20	30	25	54.0	50.5	54.0	39.5	2330 (1 + 1)	1.25	
47C	G-K-L-N	1600 F Oil 350 F	0.590	23.9	20	25	25	30	64.0	55.5	52.5	52.0	2440 (2 + 2)	1.24	Spalling encountered at 2899 fps.
49C	G-K-L-N	1475 F Water 350 F	0.550	22.2	15	30	30	25	63.0	57.5	53.5	53.0	2447 (1 + 1)	1.30	Cracking and spalling.
							Table X-D								
							Explosively Clad Plate Composites								
53C	J-N(XC) (Explosively clad and rolled)	1500 F Oil 250 F (2)	0.552	22.3	50			50	58.0			47.0	2396 (1 + 1)	1.24	Slight face cracking.
55C	J-N(XE) (Explosively clad and rolled)	1500 F Oil 250 F (2)	0.613	24.8	50			50	58.0			51.0	2396 (1 + 1)	1.19	Slight face cracking.
							Table X-E								
							Weld Overlayed and Rolled Plate Composites								
A-1	Weld overlay (Hardex 45 on A)	1500 F Oil 300 F	0.525	21.2	45			55	55.0			50.0	2351 (1 + 1)	1.29	Some front cracking and back spalling.
A-2	Weld overlay (Hardex 52 on A)	1500 F Glycol-Water No temper	0.548	22.1	45			55	56.0			52.5	2296 (2 + 2)	1.22	Some front cracking; plate fractured after four rounds.

*First line = austenitizing temperature; second line = quenching medium; third line = tempering temperature.
**The hardnesses of the intermediate layers of the tricomposites and quadcomposites were estimated from other heat-treating studies.
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Table XI

Ballistic Test Results on Composites Tested With Caliber 0.50 AP M2 Projectiles at 45° Obliquity (U)

Code	Composite	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
67D-2	22-23	1500F Oil 300 F	0.299	12.0	40	60	60.0	50.5	<2188	<1.14	Front cracking and front and back spalling.
67D-1	22-23	1500 F Oil 300 F	0.354	14.3	50	50	60.0	51.0	2643 (3 + 3)**	1.16	Front cracking and front and back spalling.
67F-2	22-23	1500 F Oil 300 F	0.401	16.2	50	50	60.0	51.0	2780 (2 + 2)	1.08	Front cracking and back spalling.
67F-1	22-23	1500 F Oil 300 F	0.427	17.2	50	50	59.0	51.0	>3199	>1.20	Front cracking.
66E	20-21	1525 F Oil 300 F	0.501	20.2	50	50	59.5	49.0	>3162	--	--

*First line = austenitizing temperature; second line = quenching medium; third line = tempering temperature.
**Number of partials and completes in the average.

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Table XII

Ballistic Test Results on Differently Processed Production Composites Tested With Caliber 0.30 AP M2 Projectiles at 0° Obliquity (U)

Code	Variable	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
	A. Effects of Miscellaneous Processing Variables on Composite 20-21 (Pack 66G)										
A1	Base—ground, then hardened, tempered immediately.	1500 F Oil 275 F	0.260	10.50	50	50	60.0	50.0	2483 (2+2)**	1.50	Slight rear cracking.
A2	Same as A1 but delayed 1 day before tempering.	1500 F Oil 275 F	0.259	10.45	55	45	61.0	51.0	2554 (3+3)	1.54	Bad front and rear cracking; spalling and separation at bond.
B2	Same as A1 but ground after hardening.	1500 F Oil 275 F	0.310	12.50	50	50	60.0	49.0	2526 (3+3)	1.35	Slight rear spalling.
C2	Same as A1 but not tempered.	1500 F Oil	0.260	10.50	50	50	61.5	50.0	2579 (2+2)	1.55	Some rear spalling.
D2	Same as A1 but rear face only shot-blasted.	1500 F Oil 275 F	0.263	10.60	40	60	61.0	51.0	2552 (3+3)	1.52	Some separation at bond.
D3	Same as A1 but rear face not touched.	1500 F Oil 275 F	0.264	10.60	50	50	55.0	40.0	2488 (3+3)	1.49	Slight front cracking.
E2	Same as A1 but front face only shot-blasted.	1500 F Oil 275 F	0.264	10.60	50	50	58.0	53.0	2424 (3+3)	1.45	
E3	Same as A1 but front face not touched.	1500 F Oil 275 F	0.262	10.55	55	45	57.0	50.5	2510 (2+2)	1.50	Some rear cracking and spalling.
F2	Same as A1 then treated at -320 F and at 275 F.	1500 F Oil 275 F -320 F 275 F	0.257	10.40	50	50	60.0	51.0	2445 (3+3)	1.48	
G2	Intermediate temper at 1100 F.	1500 F Oil 1100 F Air 1500 F (flash) Oil 275 F	0.260	10.50	50	50	60.0	50.0	<2231	<1.34	Stopped testing after 4 rounds

(Continued)

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Table XII (Continued)

Ballistic Test Results on Differently Processed Production Composites Tested With Caliber 0.30 AP M2 Projectiles at 0^{o} Obliquity (U)

Code	Variable	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	Layer Thickness Proportions, % Rear	Plate Hardness, R_C Front	Plate Hardness, R_C Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
G3	Intermediate temper at 1290 F.	1500 F Oil 1290 F Air 1500 F (flash) Oil 275 F	0.258	10.40	50	50	61.0	53.0	2463 (3+3)	1.49	Some front cracking and spalling
		B. Shot-Penning Experiments on Composite 9-10 (Pack 65G)									
56C	Base—not shot-peened.	1500 F Oil 250 F (2)	0.304	12.2	50	50	62.0	52.0	2679 (2+2)**	1.46	Rear plate cracking and spalling.
57C	Shot-peened front face.	1500 F Oil 250 F (2)	0.303	12.2	60	40	66.0	53.0	2707 (3+3)	1.47	Rear plate cracking and spalling.
58C	Shot-peened rear face.	1500 F Oil 250 F (2)	0.305	12.3	70	30	62.0	56.5	2716 (2+2)	1.48	Rear plate cracking and spalling.
59C	Shot-peened front and rear faces.	1500 F Oil 250 F	0.303	12.2	55	45	64.0	55.0	2724 (2+2)	1.49	Rear plate cracking and spalling.

*First line = austenitizing temperature; second line = quenching medium; third line = tempering temperatur

**Number of partials an(ompletes in the average.

Table XIII

Ballistic Test Results on Differently Processed Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Code	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	M	Rear	Plate Hardness R_C Front	M	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
	Table XIII-A											
	Effects of Tempering Variations on Composite 20-21 (Pack 66E)											
66EA	1500 F Glycol-water 275 F	0.537	21.6	45		55	60.0		50.0	2375 (2 + 2)**	1.28	Some front and rear cracking.
66EB	1500 F Glycol-water 275 F + 275 F	0.535	21.5	45		55	60.0		50.0	2367 (3 + 3)	1.28	Slight front and rear cracking.
66EC	1500 F Glycol-water 275 F (4 hr)	0.538	21.7	45		55	58.0		49.0	2339 (3 + 3)	1.26	Some front and rear cracking.
66ED	1500 F Glycol-water 300 F	0.534	21.5	45		55	59.5		48.0	2283 (2 + 2)	1.24	Slight front and rear cracking.
66EE	1500 F Glycol-water 350 F	0.530	21.4	45		55	57.5		49.0	2316 (2 + 2)	1.26	Some rear cracking.
	Table XIII-B											
	Effects of Rapid Heat Treatment on Composite 22-23 (Pack 67A) (Preliminary Tests)											
67AB-3	1600 F Oil (3 cycles) 300 F	0.636	25.8	50		50	62.0 (both ends softer)		50.5	2456 (1 + 1)	1.19	Plate not uniformly hardened. Plate broke in half after six rounds.
67AB-4	1600 F Oil (3 cycles) 300 F -320 F 300 F	0.636	25.8	50		50	60.0 (both ends softer)		50.5	2560 (2 + 2)	1.24	Plate not uniformly hardened. Some front and rear cracking.
67AB-8	1475 F Oil 300 F	0.633	25.7	50		50	60.0 (both ends softer)		50.0	2528 (1 + 1)	1.23	Plate not uniformly hardened. Some rear cracking.
67AB-5	1475 F Oil (3 cycles) 300 F -320 F 300 F	0.633	25.7	50		50	62.0 (both ends softer)		52.0	2515 (1 + 1)	1.22	Plate not uniformly hardened. Some front and rear cracking.

(Continued)

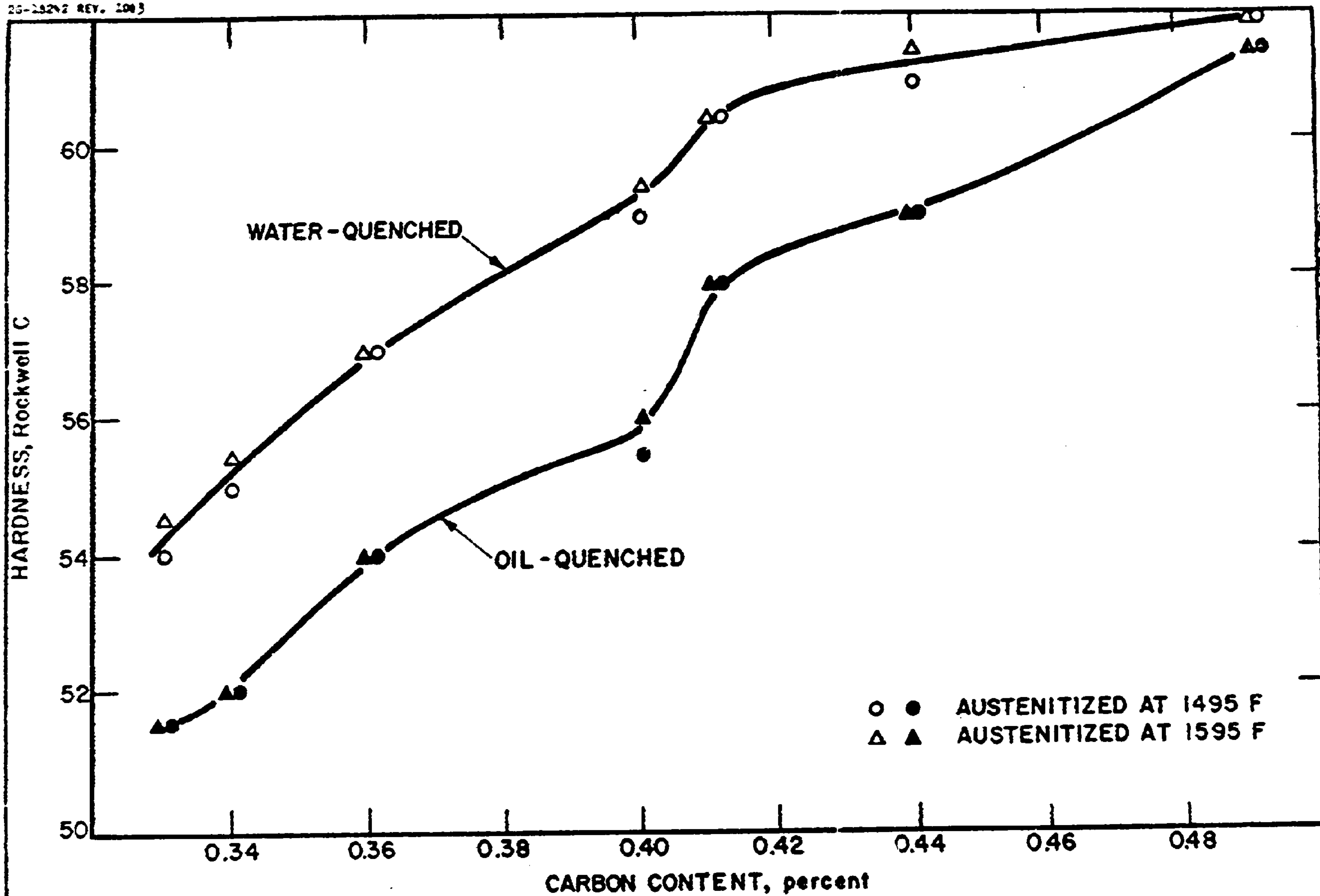
Table XIII (Continued)

Ballistic Test Results on Differently Processed Composites Tested With Caliber 0.50 AP M2 Projectiles at 0° Obliquity (U)

Code	Heat Treatment*	Thickness, inch	Areal Density, lb/ft^2	Layer Thickness Proportions, % Front	M	Rear	Plate Hardness, R_C Front	M	Rear	V_{50} Protection Ballistic Limit, fps	Merit Rating	Remarks
67AB-7	1600 F Oil (3 cycles) 300 F -320 F 300 F	0.623	25.2	50		50	59.0		50.0	2621 (1 + 1)	1.29	Some front and rear cracking.
67AB-9	1475 F Oil (3 cycles) 300 F	0.619	24.8	50		50	60.0		50.0	2732 (2 + 2)	1.36	Some front cracking and back spalling.
67AB-2	1000 F Oil (3 cycles) 300 F	0.626	25.4	50		50	60.0		50.0	2708 (2 + 2)	1.33	Some front cracking, back spalling, and bond separation.
6-E-13 Lab Tri-composite	1475 F Oil (3 cycles) 300 F	0.644	26.1	35	35	30	60.0 (both ends softer)	56.0	42.0	2650 (1 + 1)	1.28	Plate not uniformly hardened. Some front and rear cracking and rear bond separation.
6-E-13 Lab Tri-com-posite	1475 F Oil (3 cycles) 300 F -320 F 300 F	0.626	25.4	35	35	30	59.0	56.0	42.0	> 2707 (1 HP)	> 1.32	Bond separation and plate cracking.

*First line = austenitizing temperature; second line = quenching medium; third line = tempering temperature (30 minutes unless otherwise noted).
**Number of partials and completes in the average.

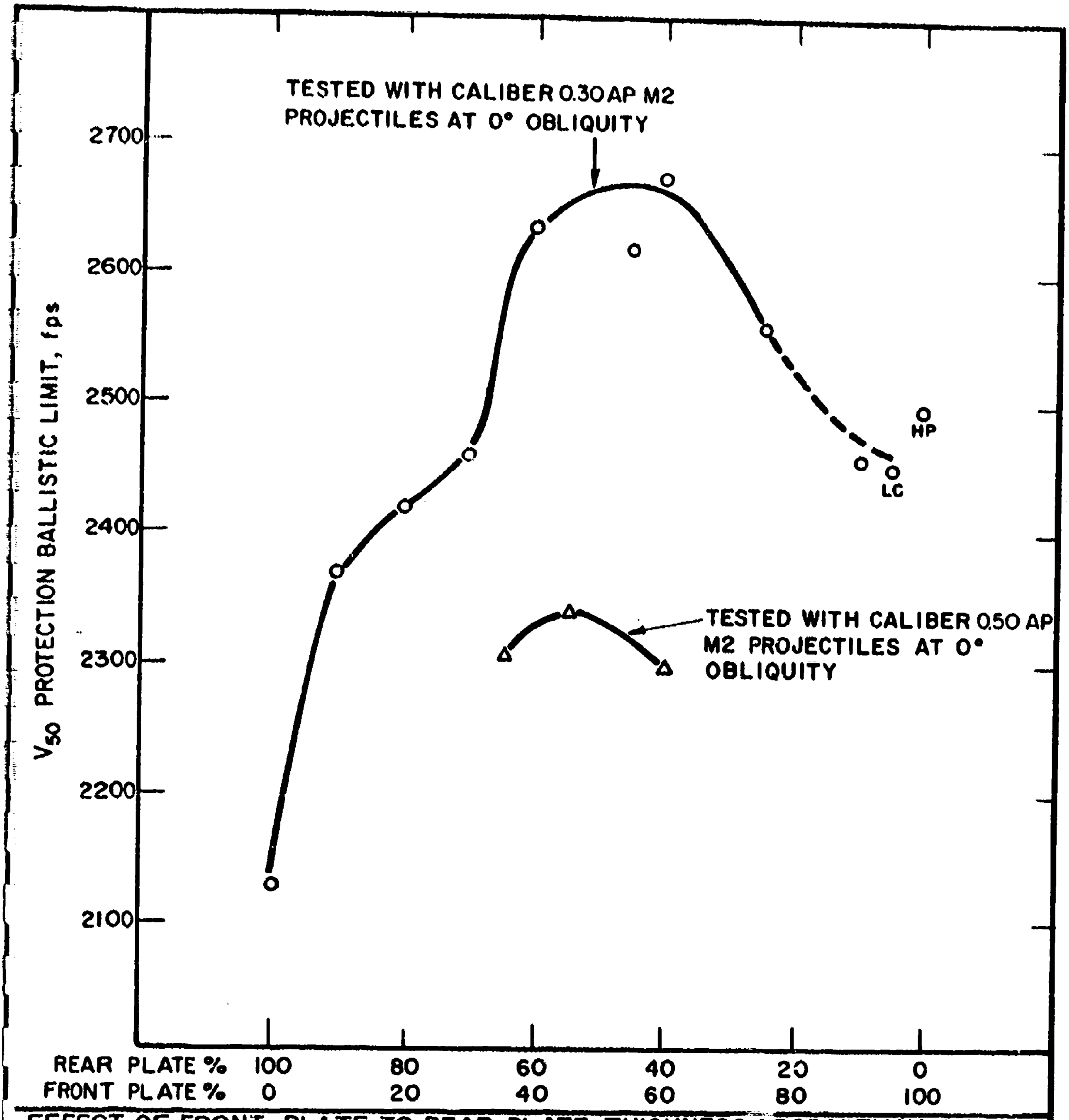
UNCLASSIFIED



EFFECT OF CARBON CONTENT ON THE AS-QUENCHED HARDNESS OF 1/2-INCH-THICK GRADIENT-FURNACE SPECIMENS OF 0.75Mn, 1.00Ni, 0.50Cr, 0.50Mo STEEL

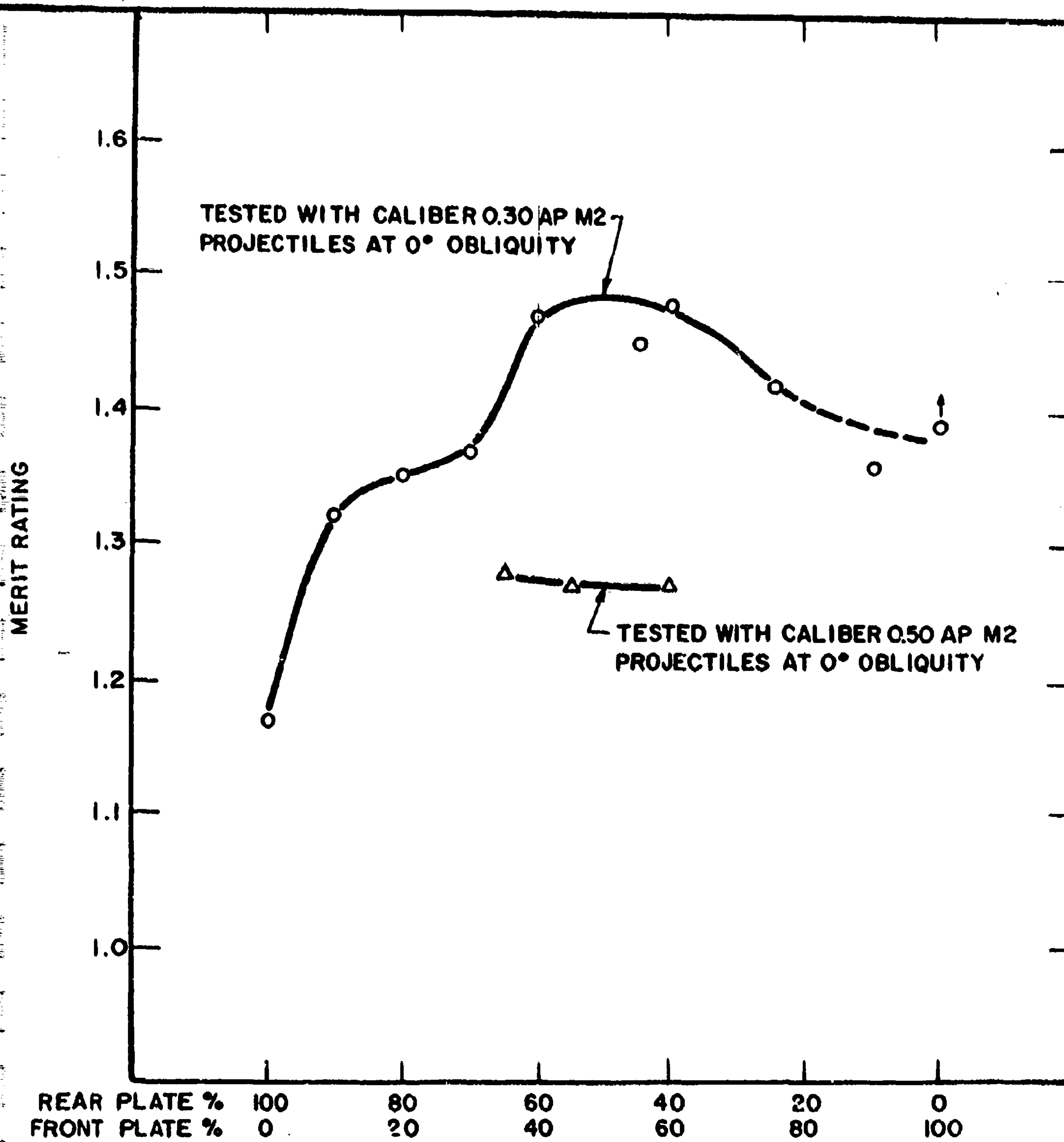
FIGURE NO. 1

UNCLASSIFIED



EFFECT OF FRONT-PLATE TO REAR-PLATE THICKNESS PROPORTIONS ON THE BALLISTIC LIMIT OF 0.3- AND 0.5-INCH-THICK PLATES OF COMPOSITE 9-10

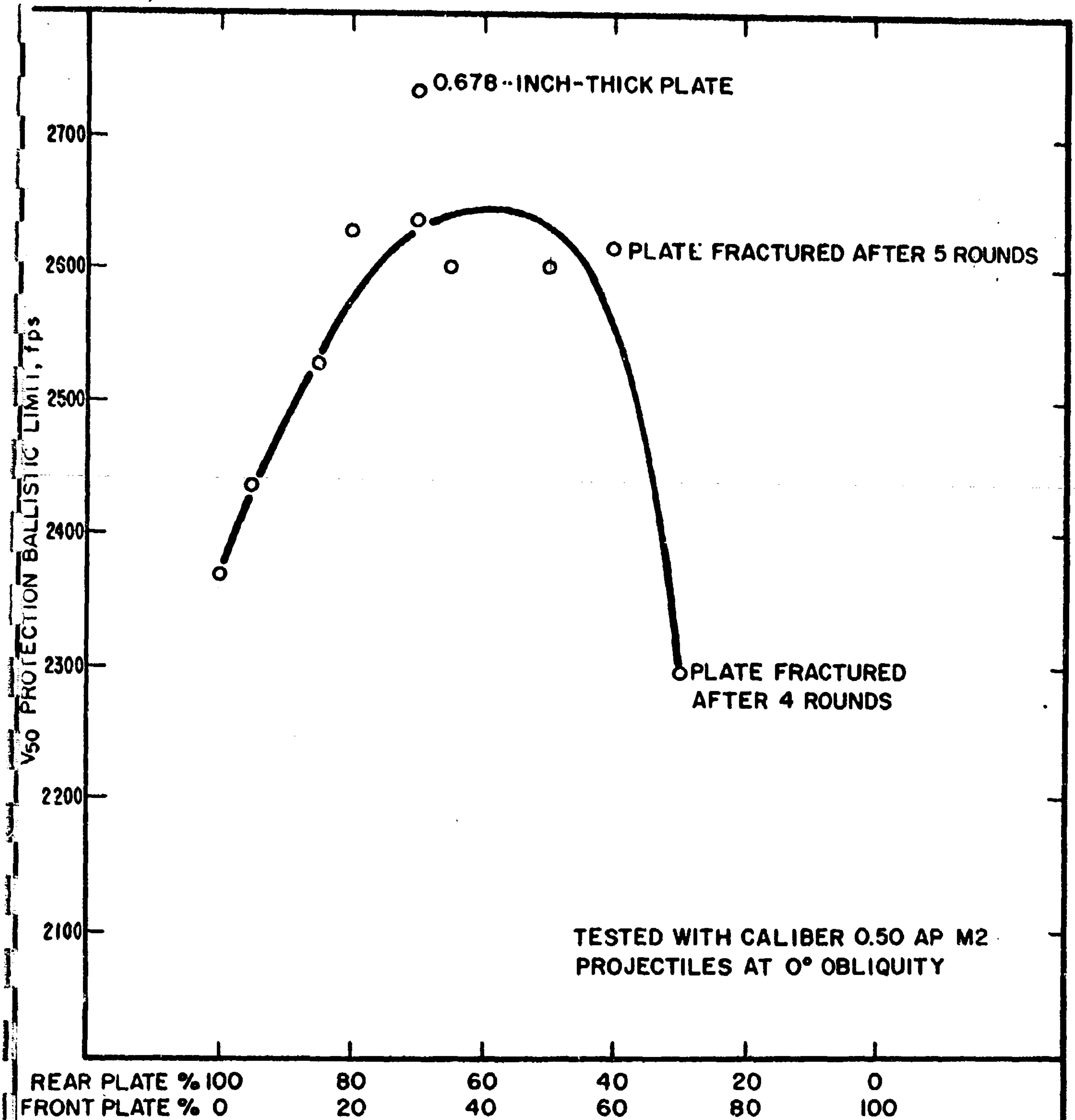
FIGURE NO. 2



EFFECT OF FRONT-PLATE TO REAR-PLATE THICKNESS PROPORTIONS ON THE MERIT RATING OF 0.3- AND 0.5-INCH-THICK PLATES OF COMPOSITE 9-10

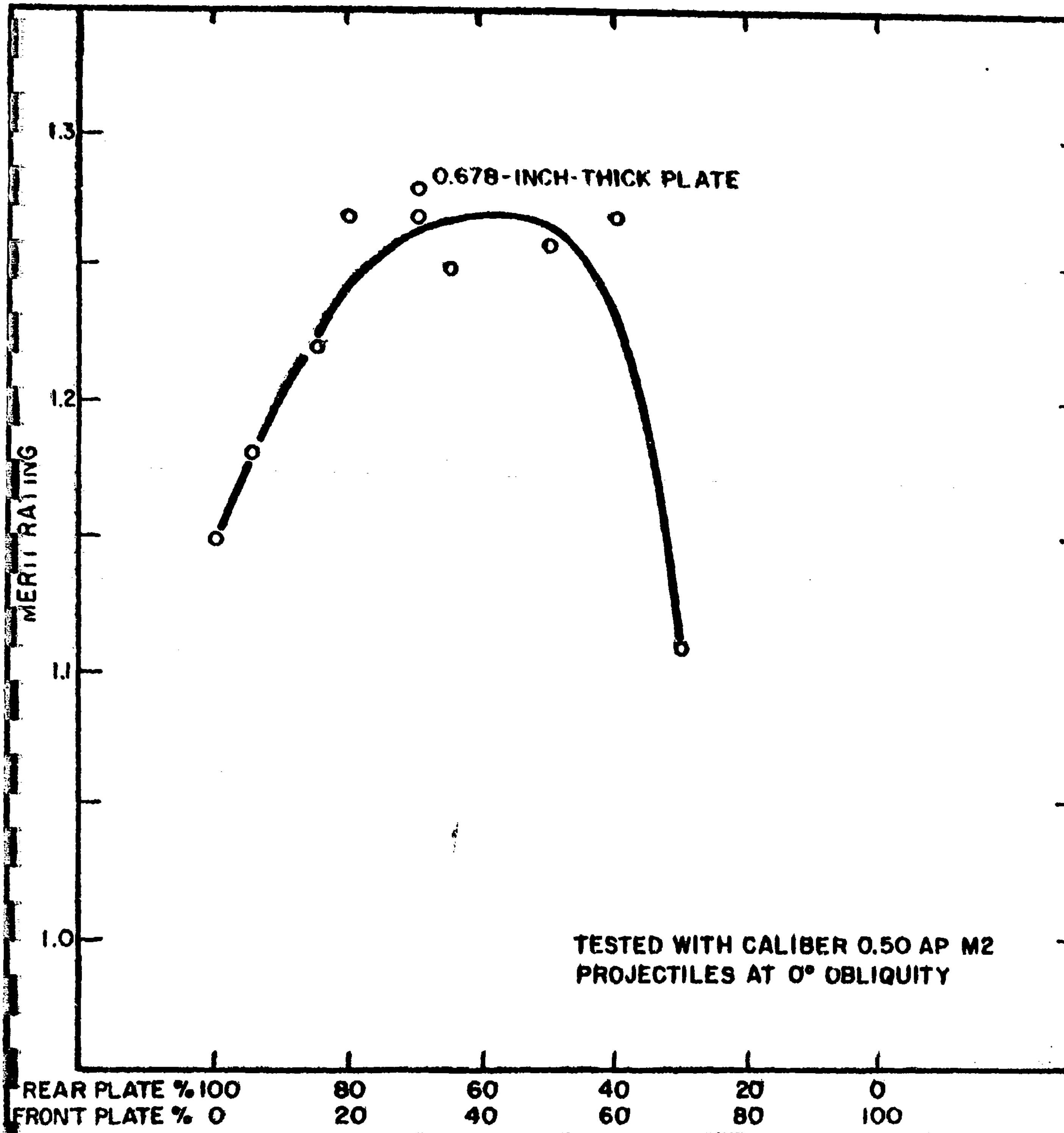
FIGURE NO. 3

G-10242 REV. 1063



EFFECT OF FRONT-PLATE-TO-REAR-PLATE THICKNESS PROPORTIONS ON THE BALLISTIC LIMIT OF 0.640-INCH-THICK PLATES OF COMPOSITE 22-21

FIGURE NO. 4



EFFECT OF FRONT-PLATE-TO-REAR-PLATE THICKNESS PROPORTIONS ON THE MERIT RATING OF 0.640-INCH-THICK PLATES OF COMPOSITE 22-21

FIGURE NO. 5

Figure 6(C) Fragments recovered from a caliber 0.50 armor-piercing projectile that struck 0.636-inch-thick dual-hardness steel plate of Composite 22-21 at a velocity of 2387 fps (partial penetration). The front (hard) face comprised only 5 percent of the total plate thickness. Approximately X1.

P-7753A-1 Figure 6(C)

A B

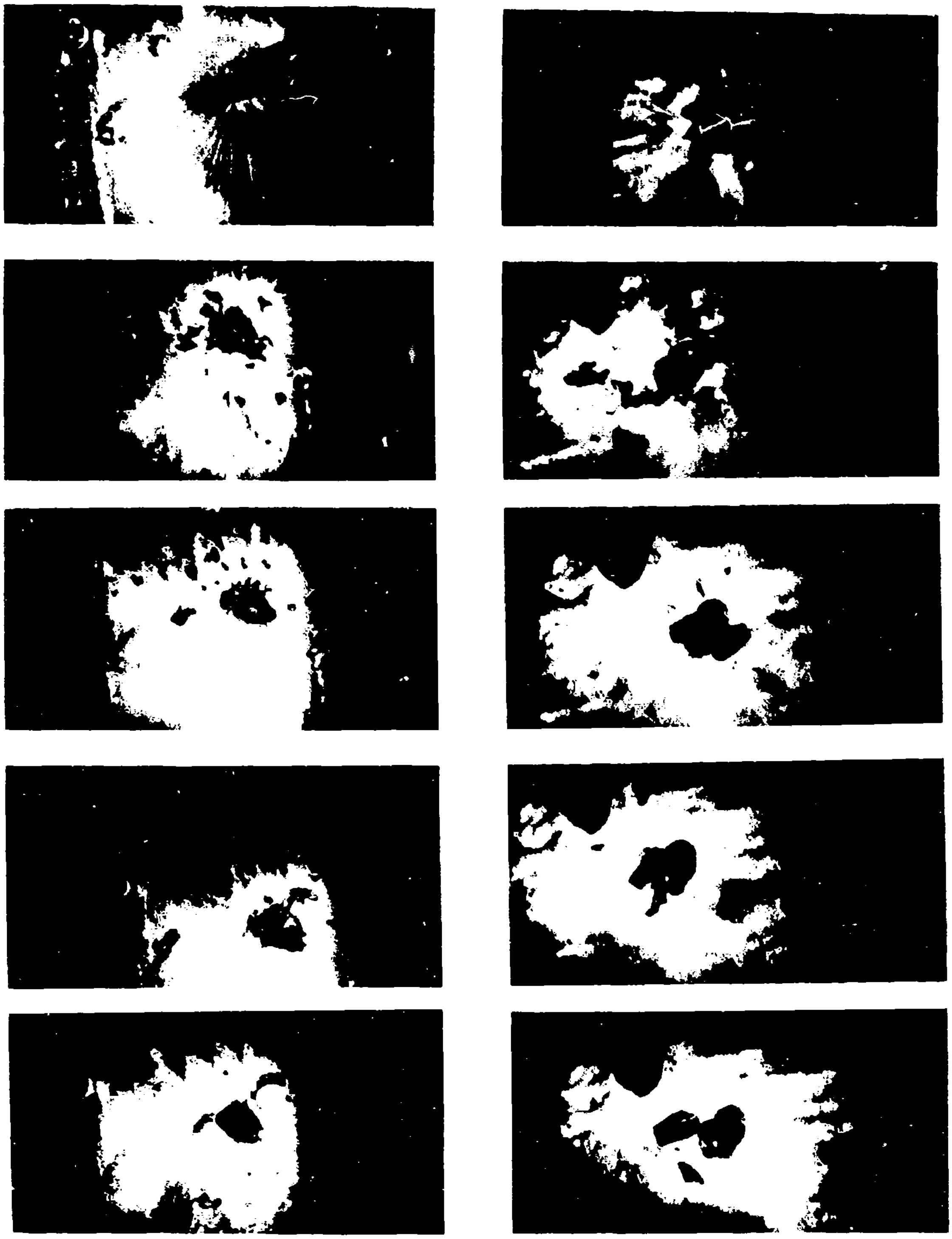


Figure 7 Complete-penetration behavior (top to bottom) of two caliber 0.50AP M2 projectiles during impact on 0.639-inch-thick dual-hardness steel plate of Composite 22-21. X1/2

Roll 1
Roll 2

Figure 7A, B

A B

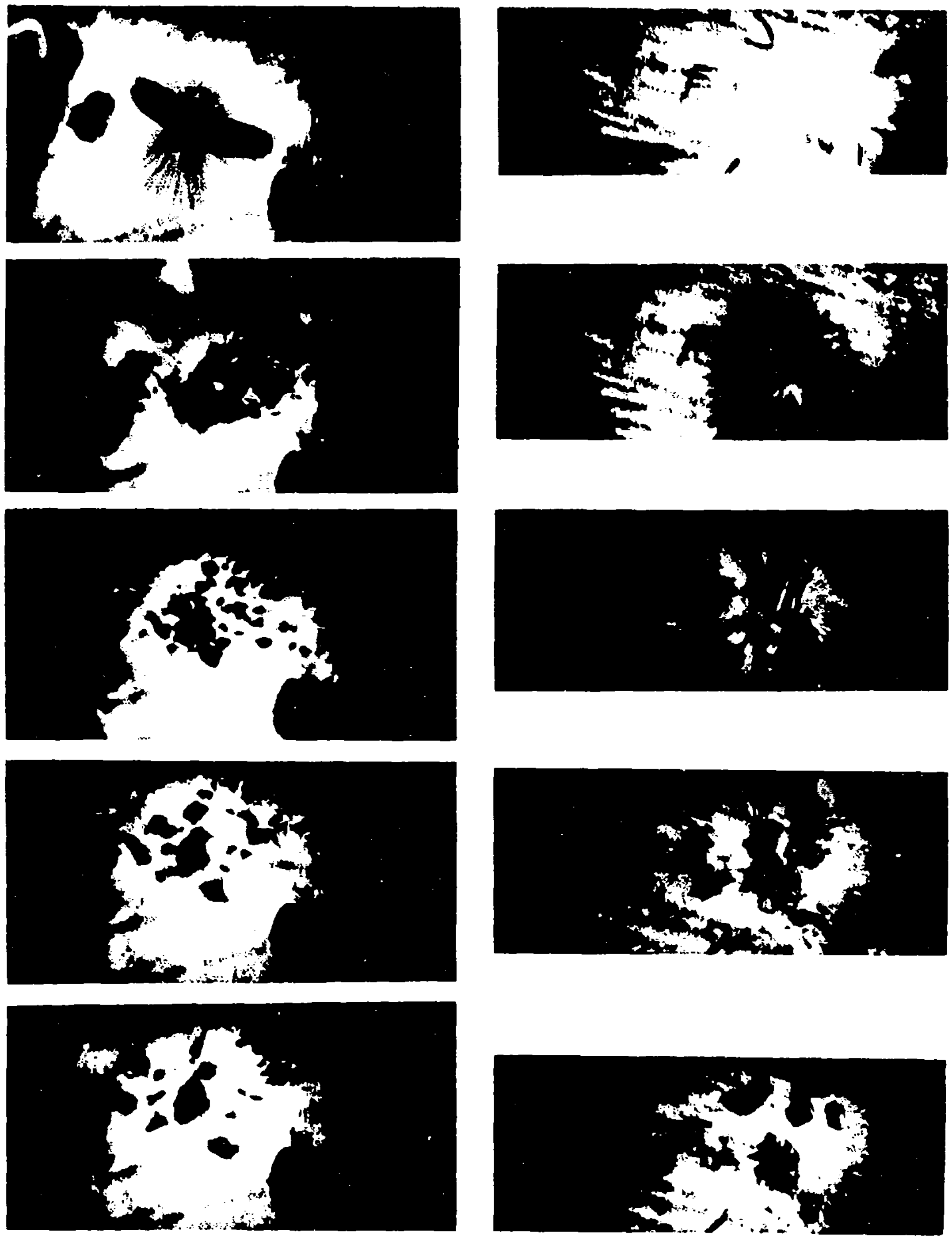
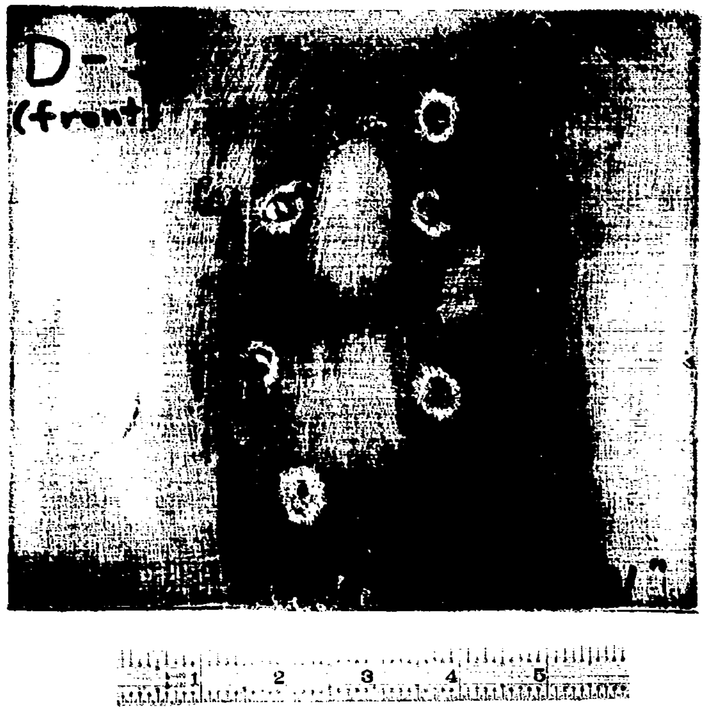


Figure 8 Partial-penetration behavior (top to bottom) of two caliber 0.50AP M2 projectiles during impact on 0.639-inch-thick (left) and 0.636-inch-thick (right) dual-hardness steel plates of Composite 22-21. X1/2

Roll 3
Roll 4

Figure 8A, B



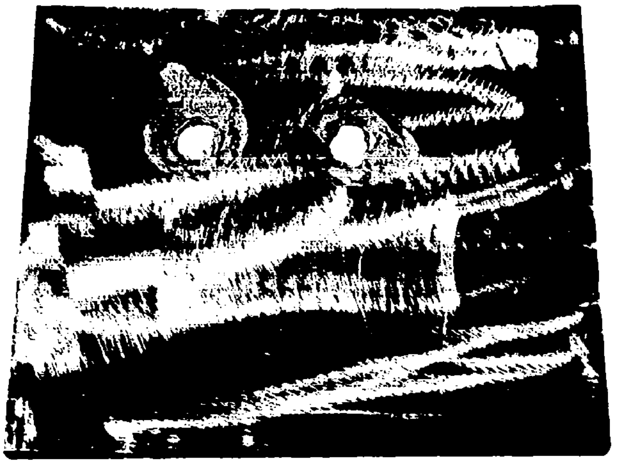
A. Front face (58.0Rc)

B. Rear face (53.0Rc)

Figure 9(C) Composite D-3 (0.281-inch thick) Roll-bonded. Tested with caliber 0.30AP M2 projectiles at 0° obliquity. Merit rating = 1.41. X1/2

P-6760A-1
P-6760A-2

A. Bicomposite G-11 (0.585-inch thick). Front spalling and separation at bondline caused by a poor bond and possibly enhanced by too great a difference between the hardnesses of the front and rear plates (64.0Rc and 42.0Rc).

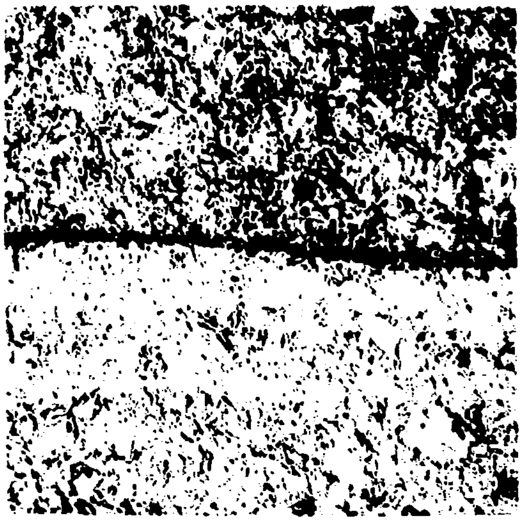


B. Bicomposite J3-N3 (0.575-inch thick). Open-hearth quality and rolled "cold." Rear face (52.0Rc). Note large back spalls.

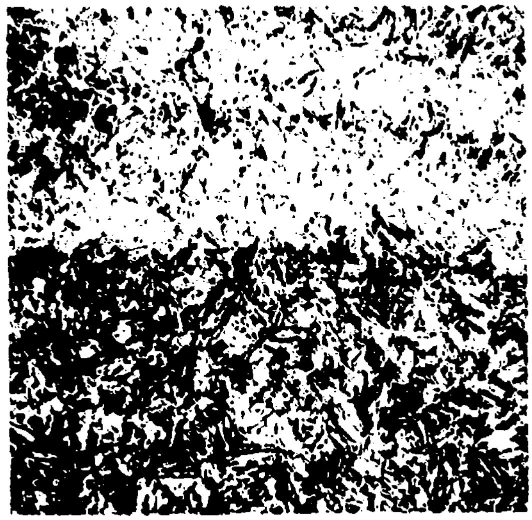
Figure 10 Selected plate composites after being tested with caliber 0.50AP M2 projectiles at 0° obliquity. X1/3

P-7498A-18
P-7498A-16

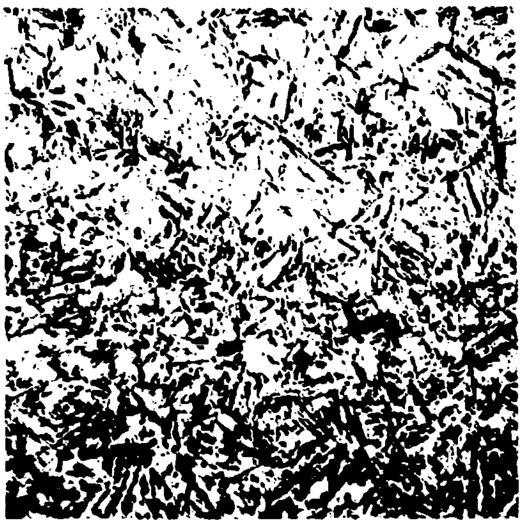
Figure 10A, B



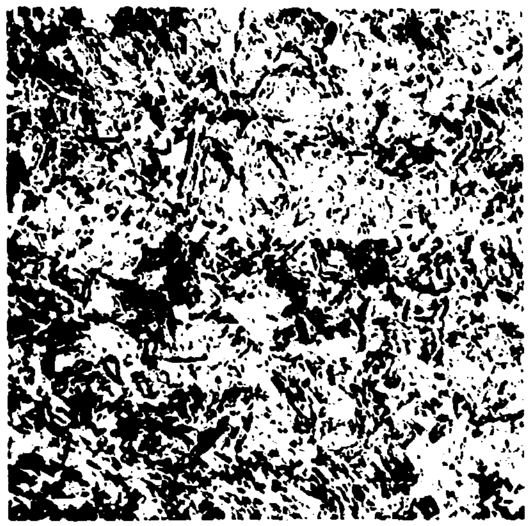
A. Composite F-A.



B. Composite H-15.



C. Composite J3-N3.

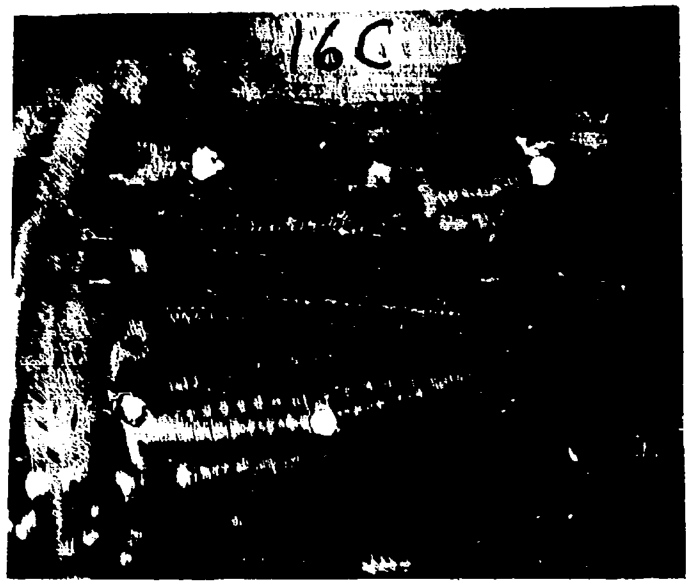


D. Composite J3-N3(LT).

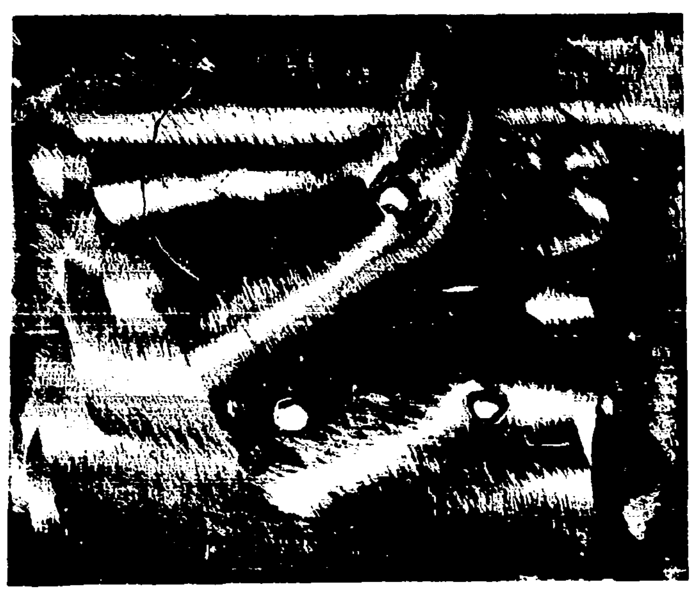
Figure 11 Bonds obtained in roll-bonded and hardened dual-hardness composites. High-carbon steel is the top layer. Nital etch. X500.

18-553A-1
18-565A-1
18-549A-1
18-550A-1

Figure 11A, B, C, D



A. Rear face (49.0Rc). Oil-quenched and tempered 0.578-inch-thick plate. Merit rating = 1.28.



B. Rear face (52.0Rc). Water quenched and tempered 0.577-inch-thick plate. Merit rating = 1.33.

Figure 12(C) Composites J3-N3 (open-hearth quality) after being tested with caliber 0.50AP M2 projectiles at 0° obliquity. X1/3

P-7498A-10
P-7498A-14

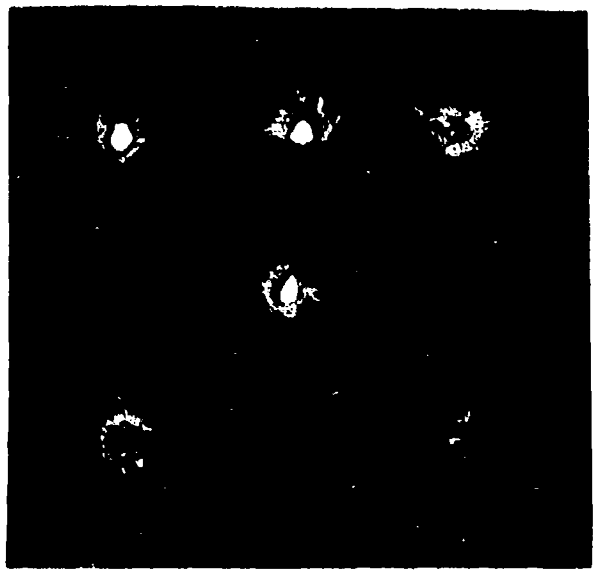
Figure 12(C) A, B

A. Front face (60.0Rc)

B. Rear face (51.5Rc)

Figure 13(C) Tricomposite K-L-N (0.575-inch-thick) after being tested with caliber 0.50AP M2 projectiles at 0^{o} obliquity. Merit rating = 1.25. X1/3

P-7498A-7
P-7498A-8



A. Front face (60.5Rc)

B. Rear face (41.0Rc)

Figure 14(C) Tricomposite 6-E-13 (0.583-inch-thick) after being tested with caliber 0.50AP M2 projectiles at 0° obliquity. Merit rating = 1.25. X1/3

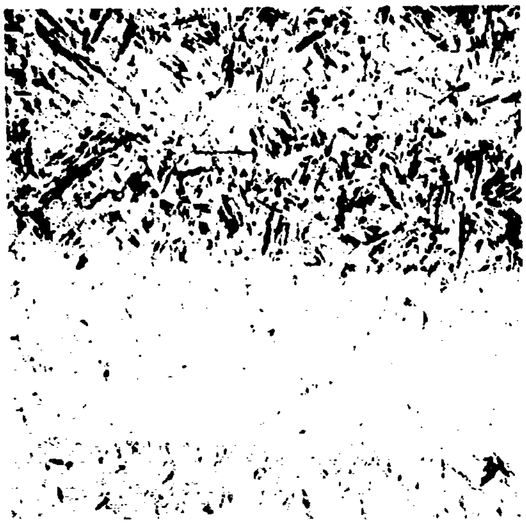
P-7498A-3
P-7498A-4

A. Front face (64.0Rc)

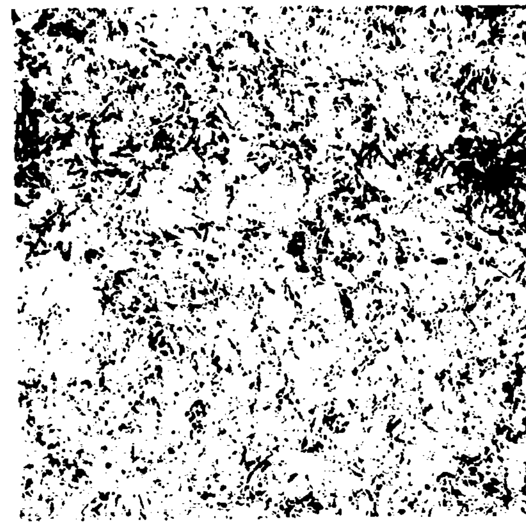
B. Rear face (40.0Rc)

Figure 15(C) Quadcomposite G-J-B-13 (0.567-inch-thick) after being tested with caliber 0.50AP M2 projectiles at 0^{o} obliquity. Merit rating = 1.22. X1/3

P-7498A-1
P-7498A-2

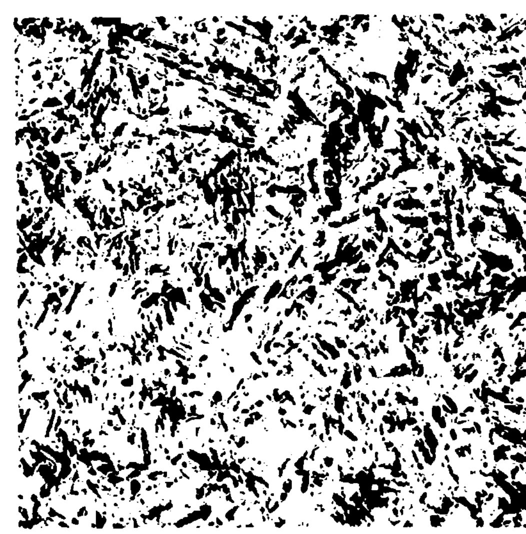


A. Composite K-L-N.



B. Composite G-L-12.

C. Composite K-L-N.



D. Composite G-L-12.

Figure 16 Bonds obtained in roll-bonded and hardened tri-composites. High-carbon steel is the top layer (A and B) medium-carbon steel is the bottom layer (A and B) and the top layer (C and D); low-carbon steel is the bottom layer (C and D). Nital etch. X500.

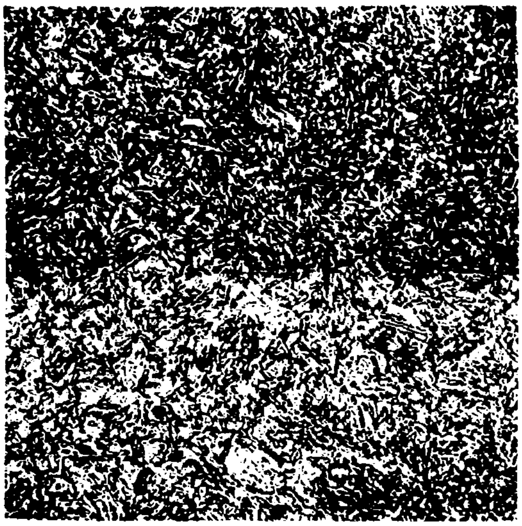
18-554A-1
18-560A-1
18-554A-2
18-560A-2

A. Tricomposite F-C-1 (0.580-inch thick).
Front face was too soft (about 50Rc).
Note cratering.

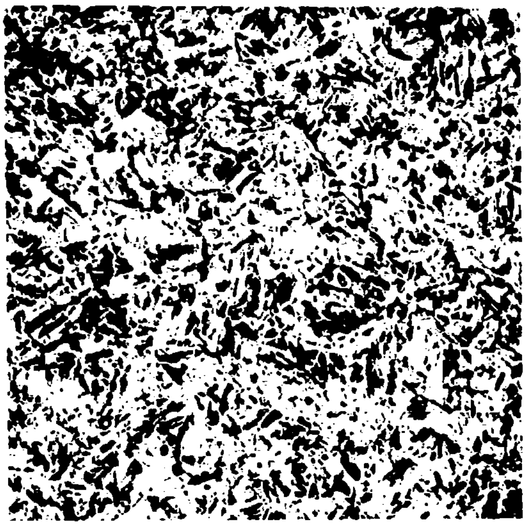
B. Tricomposite 6-E-13 (0.580-inch thick).
Rear face was too soft (39.0Rc).
Note petaling.

Figure 17 Selected plate composites after being tested with caliber 0.50AP M2 projectiles at 0° obliquity. X1/3

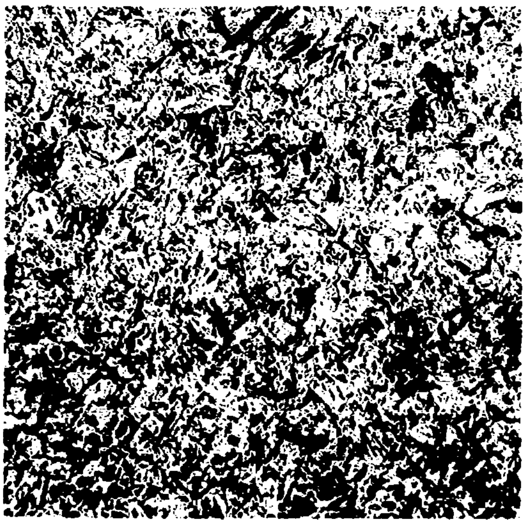
P-7498A-11
P-7498A-17



A. First production run.
Composite 9-10.



B. Second production run.
Composite 20-21.



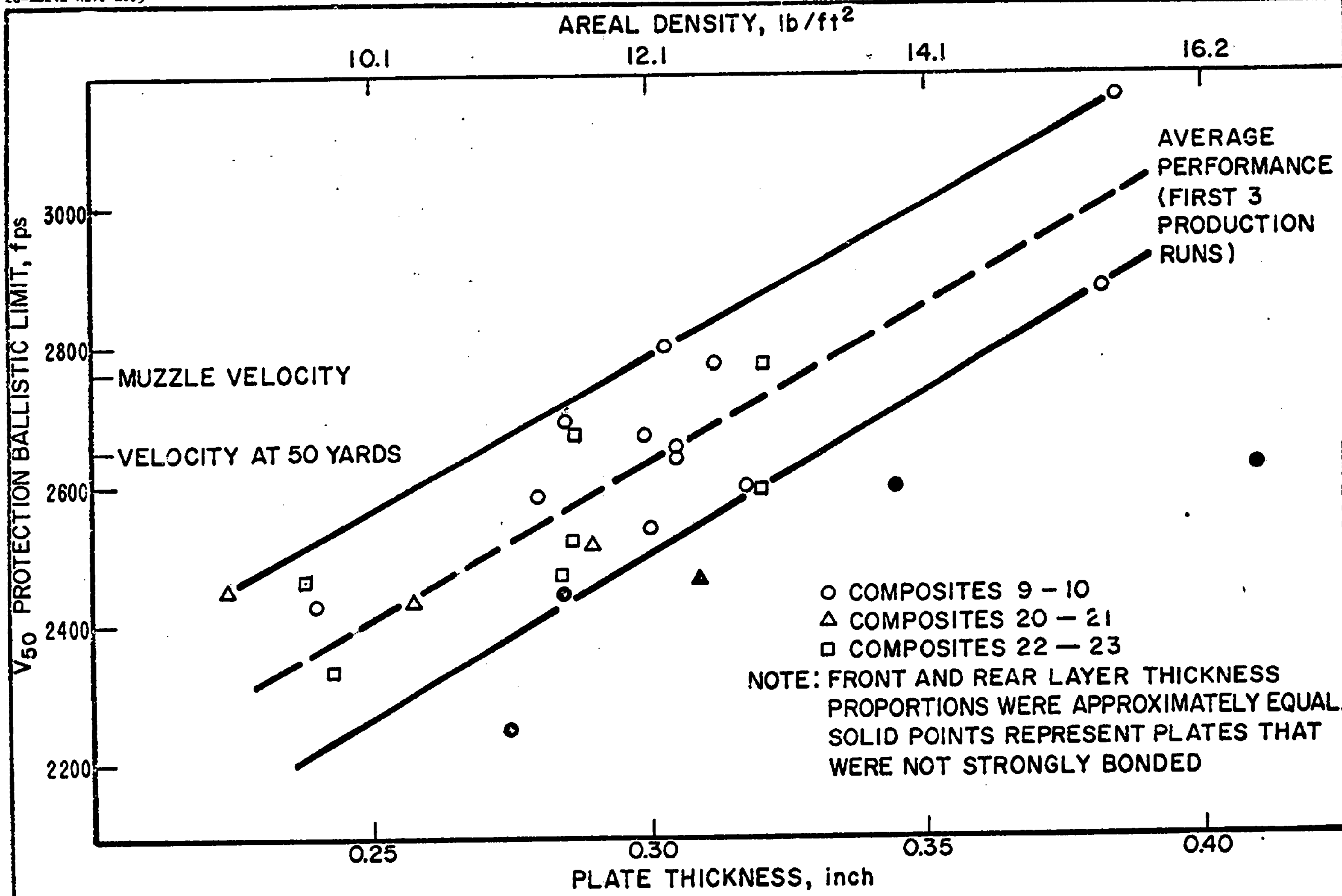
C. Third production run.
Composite 22-23.

Figure 18. Typical bonds obtained in roll-bonded and hardened production dual-hardness plate composites. High-carbon steel is the top layer. Nital and/or picral etch. X500.

18-487A-2
18-548A-1
18-605A-1

Figure 18 A,B,C

2G-18242 REV. 1063



RELATION BETWEEN PLATE THICKNESS AND BALLISTIC LIMIT (CAL 0.30 AP M2 PROJECTILES AT 0° OBLIQUITY) FOR PRODUCTION DUAL-HARDNESS COMPOSITE STEEL ARMOR (FIRST 3 PRODUCTION RUNS)

FIGURE NO. 19

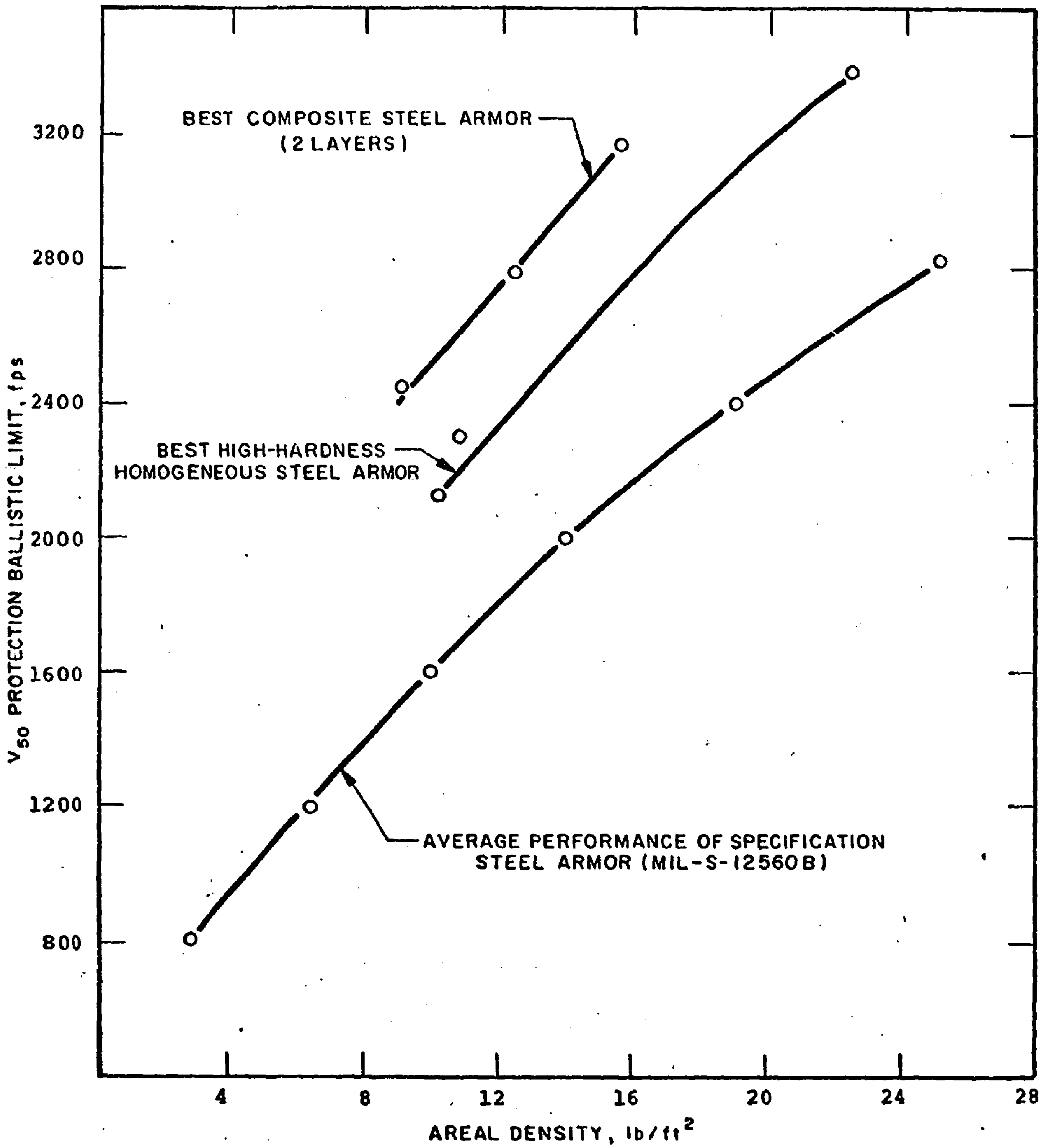
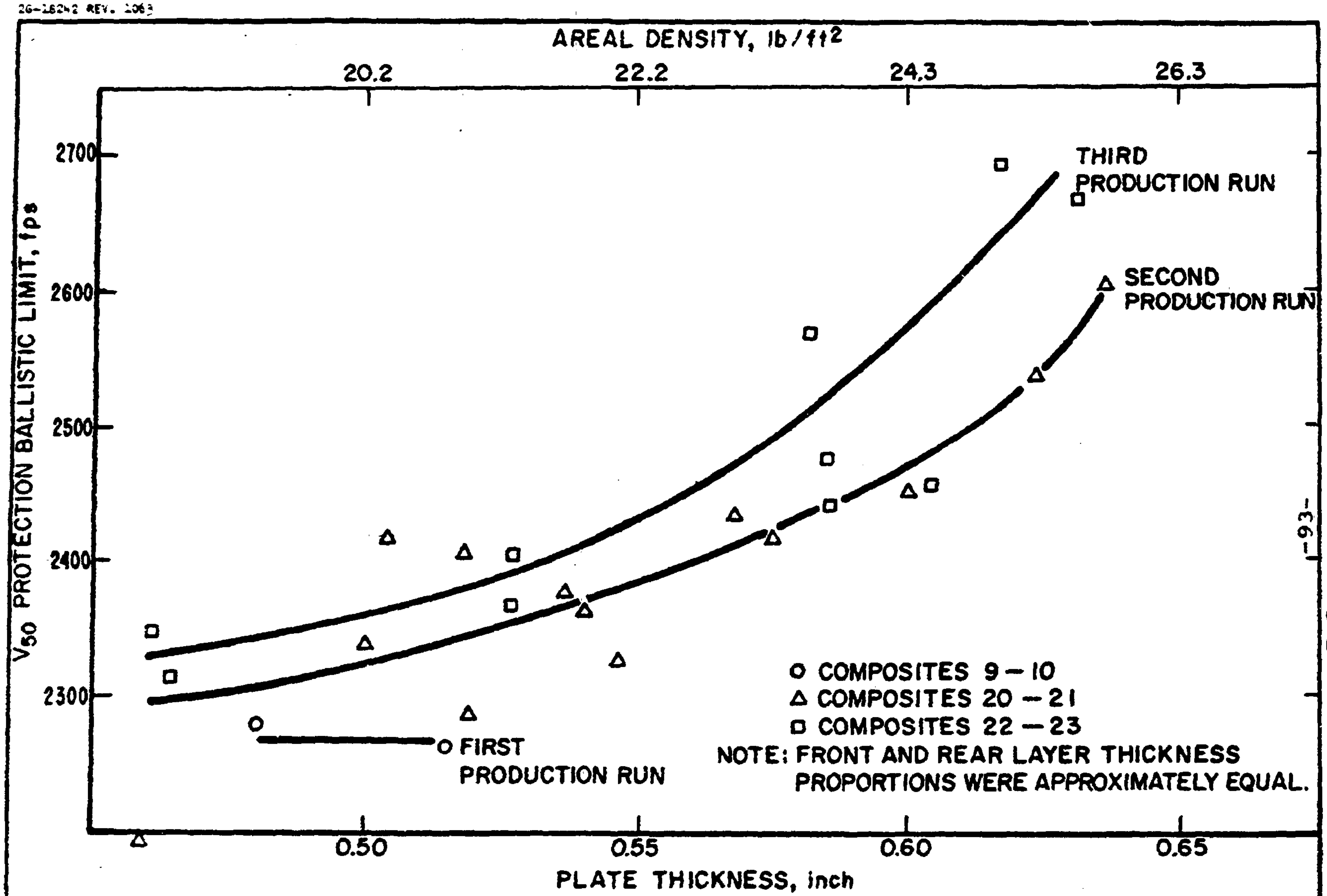


FIGURE 20 PROTECTION PROVIDED BY STEEL ARMOR AGAINST CALIBER 0.30 AP M2 PROJECTILES AT 0° OBLIQUITY

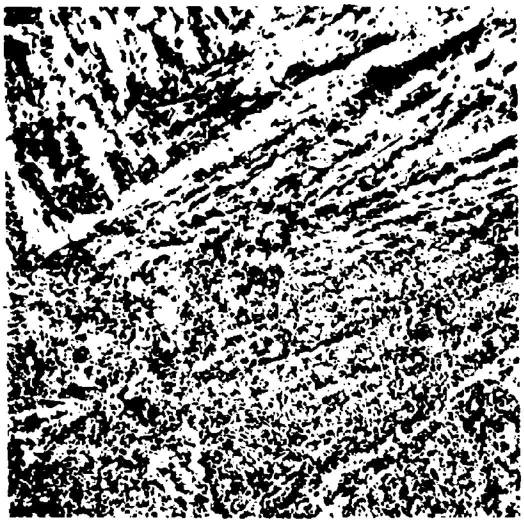
CONFIDENTIAL



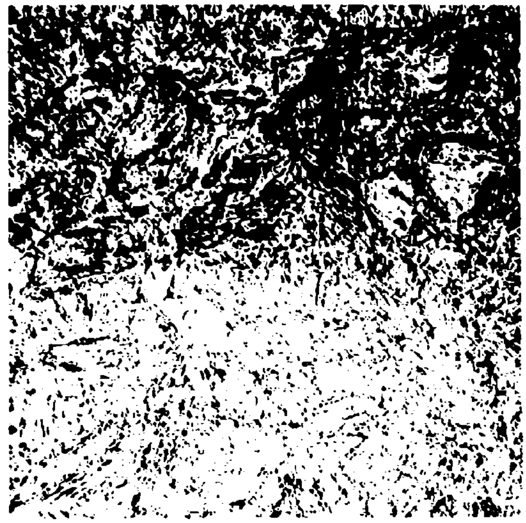
RELATION BETWEEN PLATE THICKNESS AND BALLISTIC LIMIT (CAL 0.50 AP M2 PROJECTILES AT 0° OBLIQUITY) FOR PRODUCTION DUAL-HARDNESS COMPOSITE STEEL ARMOR (FIRST 3 PRODUCTION RUNS)

FIGURE NO. 21

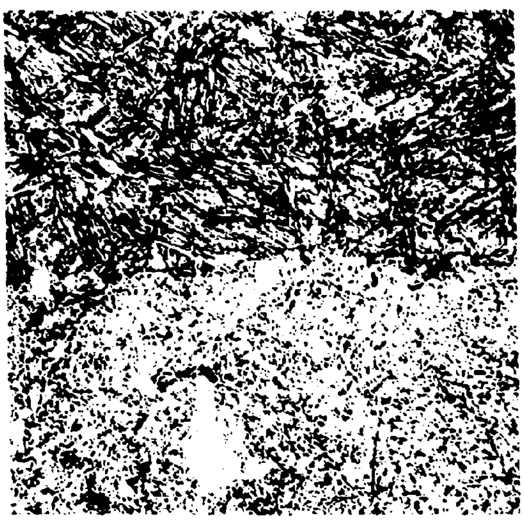
CONFIDENTIAL



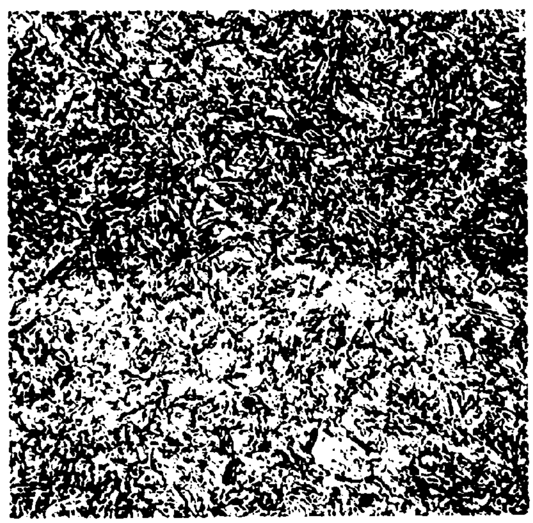
A. As-rolled and diffusion-treated.



B. As-rolled, diffusion-treated, and hardened (oil-quenched).



C. As-rolled.

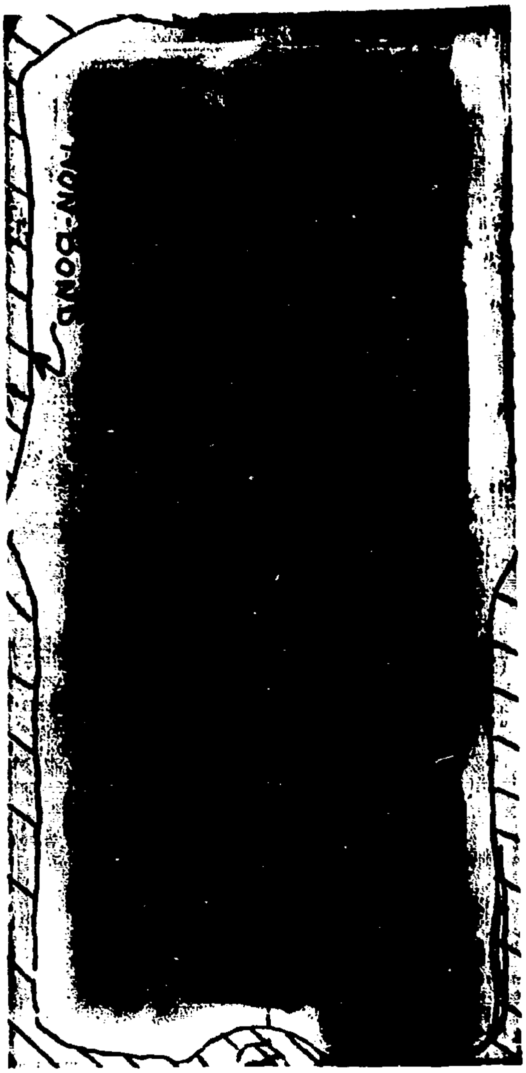


D. As-rolled and hardened (oil-quenched).

Figure 22 Bonds obtained in 7/16-inch-thick plates of Composite 9-10 (Pack 65D). High-carbon steel is the top layer. Super picral etch. X500.

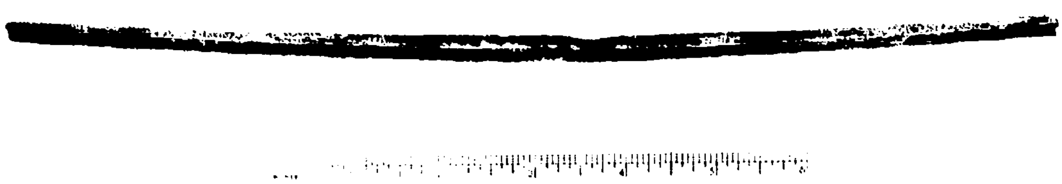
18-487A-1
18-487A-3
18-487A
18-487A-2

Figure 22A, B, C, D



A. As-bonded Composite J-N(XA) (rear view). X1/4.

B. As-bonded Composite J-N(XB) (rear view). X1/4.

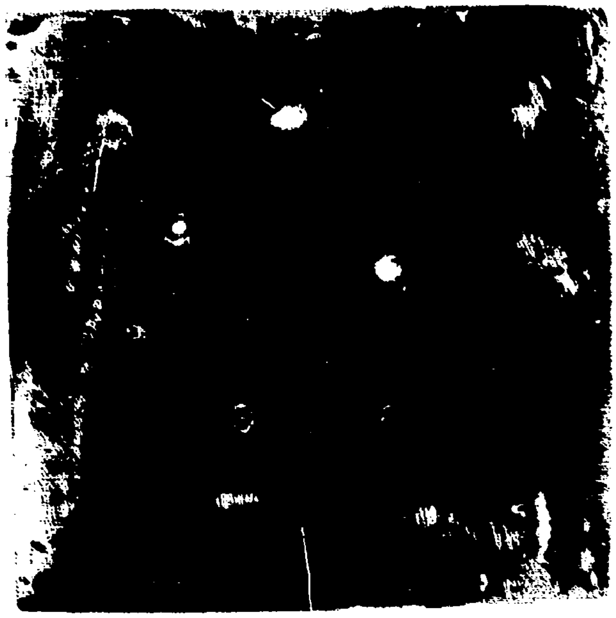


C. End view of explosively clad plate composite (note slight transverse bowing).

Figure 23 Appearance of 0.32-inch-thick explosively clad (not subsequently rolled) plate composites.

P-6902A-1
P-6902A-2
P-6902A-3

Figure 23A, B, C



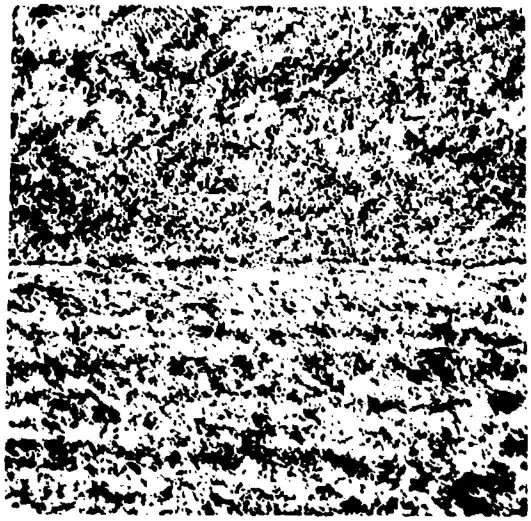
A. Front face (59.0Rc)

B. Rear face (51.0Rc)

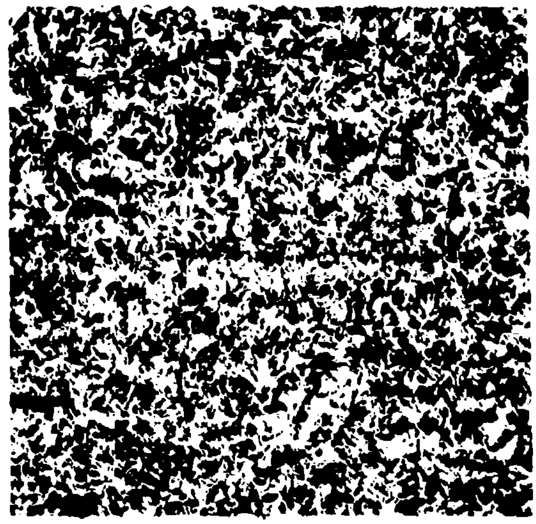
Figure 24(C) Composite J-N(XB) (0.302-inch thick). Explosively clad but not rolled. Tested with caliber 0.30AP M2 projectiles at 0° obliquity. Merit rating = 1.38. X1/3

P-7691A-1
P-7697A-2

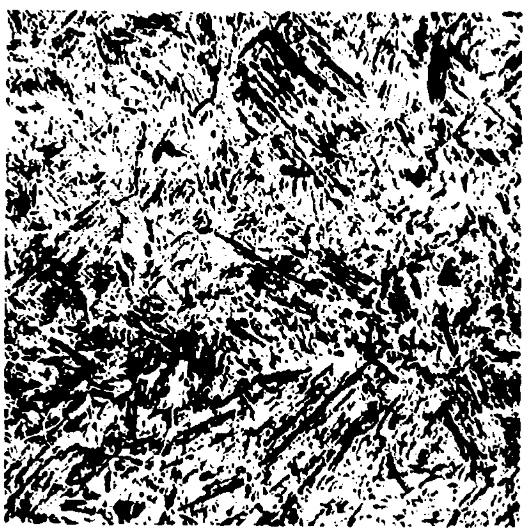
Figure 24(C) A, B



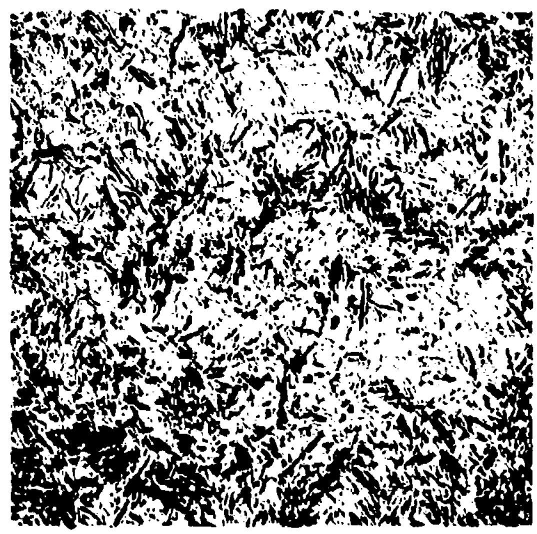
A. Composite J-N(XA) explosively clad (0.32-inch thick) and unhardened.



B. Composite J-N(XA) explosively clad (0.32-inch thick) and hardened.



C. Composite J-N(XC) explosively clad (0.88-inch thick), rolled, and hardened.



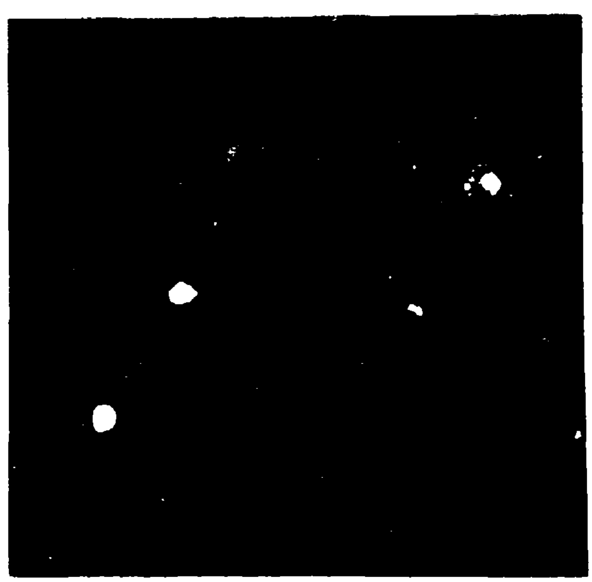
D. Composite J-N(XE) explosively clad (1.63-inch thick), rolled, and hardened.

Figure 25 Bonds obtained in explosively clad and explosively clad and rolled dual-hardness composites. High-carbon steel is the top layer. Nital etch. X500.

18-566A-1
18-566A-2
18-566A-3
18-566A-4

Figure 25A, B, C, D

A. Front face (58.0Rc)

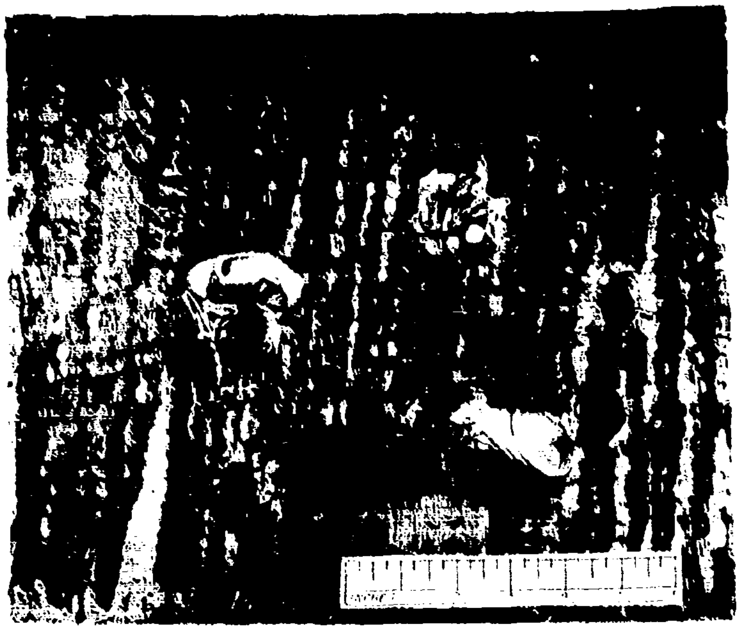


B. Rear face (47.0Rc)

Figure 26(C) Composite J-N(XC). (0.552-inch thick). Explosively clad and rolled. Tested with caliber 0.50AP M2 projectiles at 0° obliquity. Merit rating = 1.24. X1/3

P-7498A-5
P-7498A-6

Figure 26(C) A, B



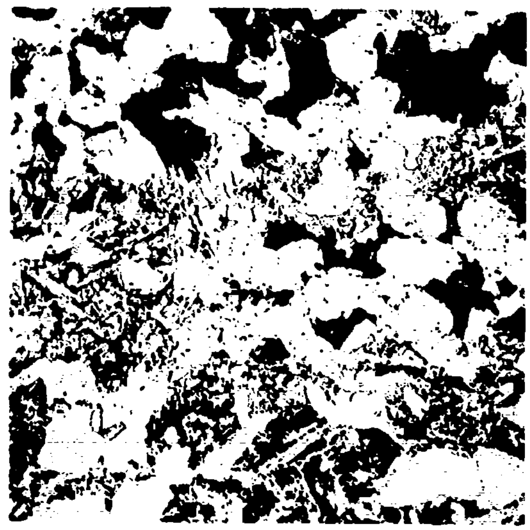
A. Front face (58.0 R_C)

B. Rear face (48.0 R_C)

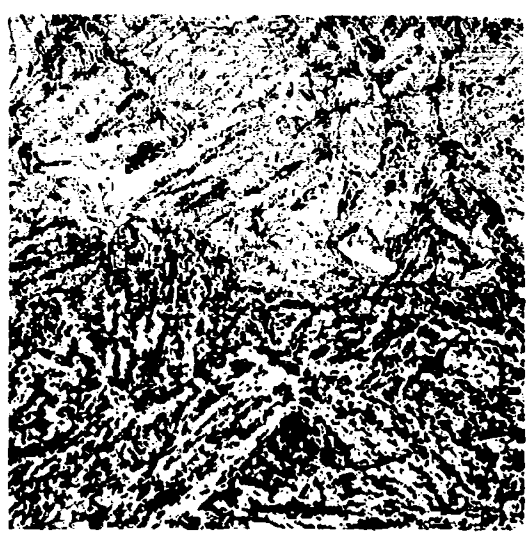
Figure 27(C). Composite J-N(XF-1) (1-1/2-inch thick). Explosively clad but not rolled. Tested at AMRA with 14.5 mm API BS-41 projectiles at 0° obliquity. Merit rating = 1.11. X1/3.

AMRA Photographs

Figure 27(C) A,B



A. Submerged-arc weld overlay. (AISI 6150)



B. Covered-electrode weld overlay. (Hardex 52)

Figure 28. Bonds obtained in weld-overlayed and rolled dual-hardness steel plate composites. Weld metal is the top layer. Nital etch. X500.

18-488A-9
18-556A-1

Figure 28 A,B

A. Weld overlay 5B. Hardex 52 on Steel N (0.323-inch thick). Tested with caliber 0.30AP M2 projectiles at 0° obliquity. Merit rating = 1.44.

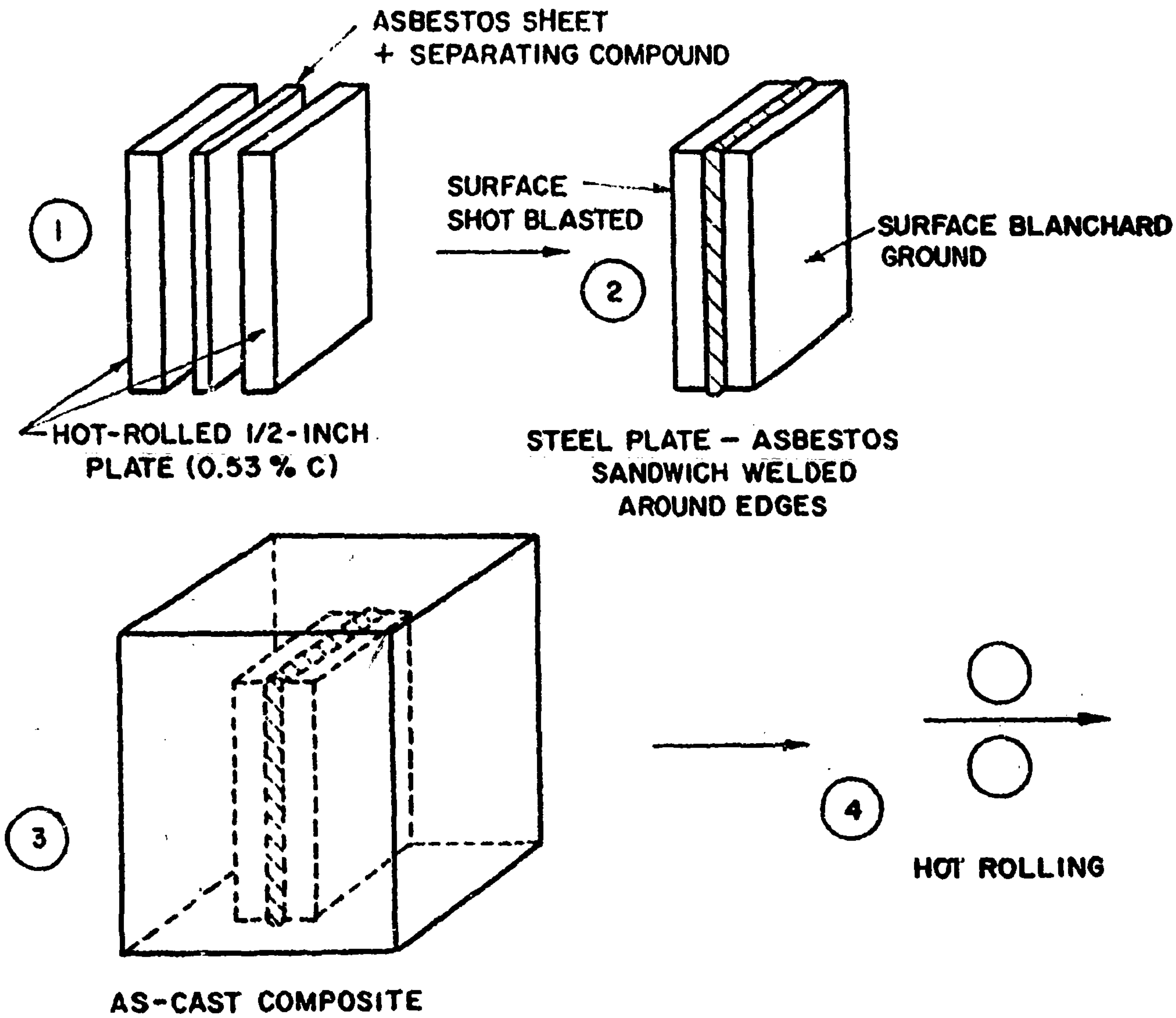
B. Weld overlay A-1. Hardex 45 on Steel A (0.525-inch thick). Tested with caliber 0.50AP M2 projectiles at 0° obliquity. Merit rating = 1.29.

Figure 29(C) Selected weld-overlayed and rolled plate composites. Front faces. X1/2

P-7690A-2
P-7690A-1

Figure 29(C) A, B

G-18242 REV. 1063



5 CUTTING AND CROSS ROLLING

6 CUTTING AND DISASSEMBLY (SEPARATION INTO TWO DUAL-HARDNESS COMPOSITES)

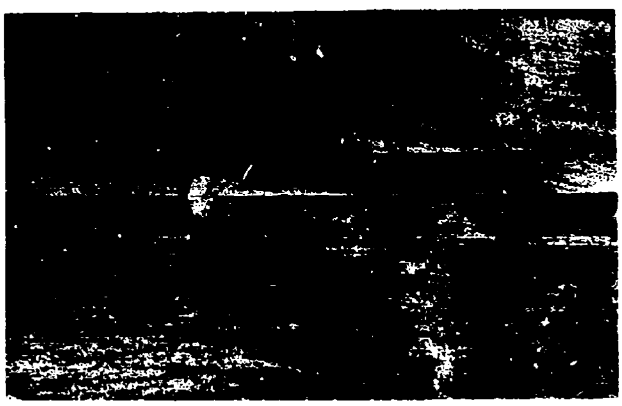
7 HEAT TREATING

SKETCH ILLUSTRATING PROCESSING STEPS FOR CAST-CLADDING EXPERIMENTS

FIGURE NO. 30

Bondline →

A. Good bond obtained in the first experiment (1-3/4-inch-thick slab of Composite 5-N. High-carbon steel is the top layer. Nital-picral etch. X500.



←Lack of bond
←Separating compound
←Lack of bond

B. Lack of bonding obtained in the second experiment (2-1/2-inch-thick slab of Composite 4-N). High-carbon steel is the double insert. Unetched. X1.

Figure 31. Bonds obtained in initial cast-cladding experiments.

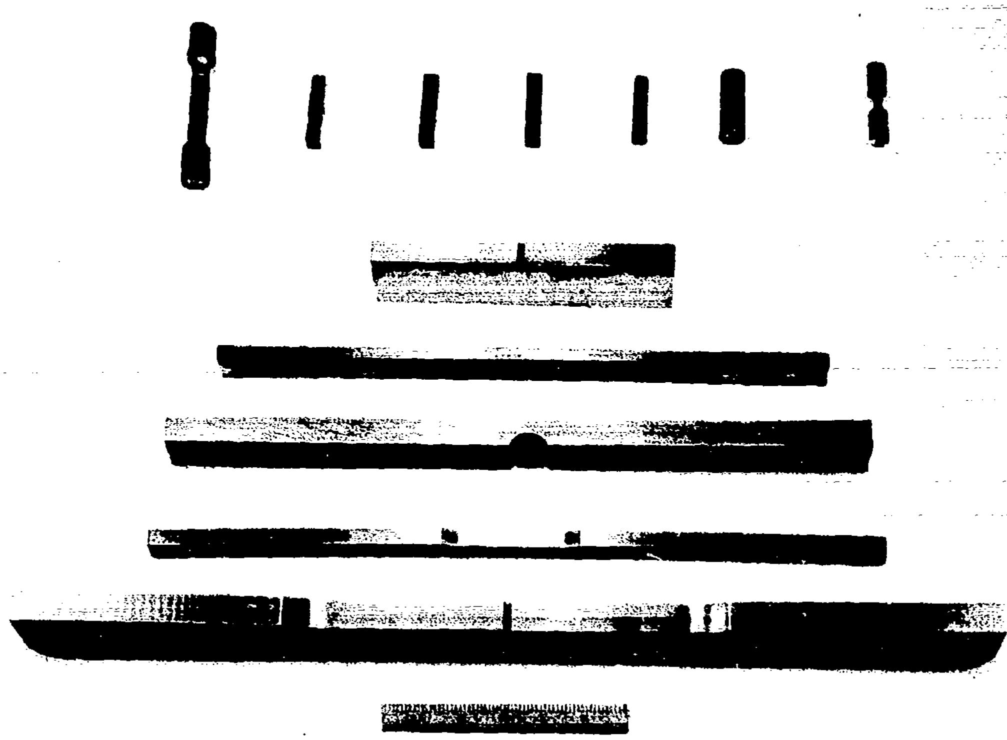
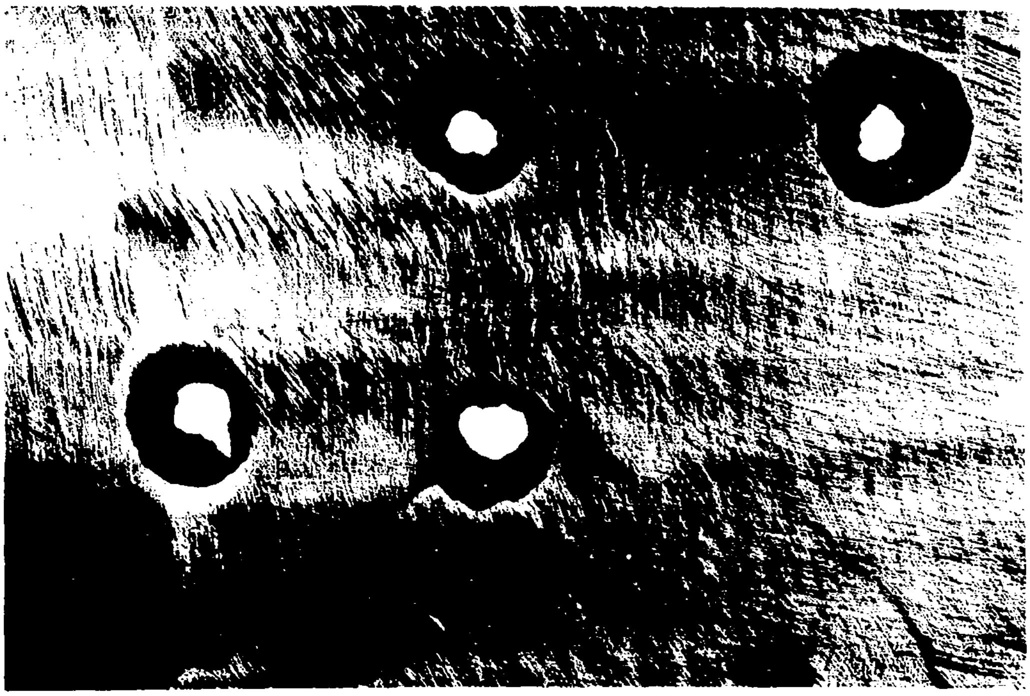
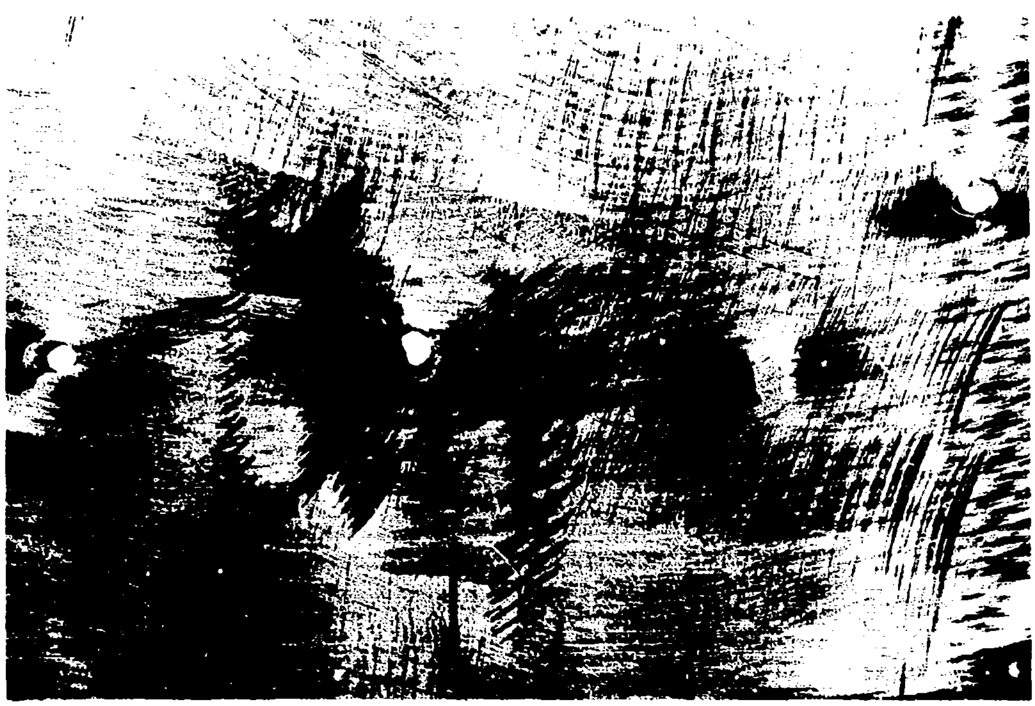


Figure 32 Mechanical-test specimens (macroetched) initially evaluated to measure the bond strength and fracture characteristics of composite steel armor. Top row (left to right): 0.505-inch-diameter tension specimen, three Charpy V-notch impact specimens, 0.4- and 0.7-inch-diameter compression specimens, and 0.20-inch-diameter through-thickness tension specimen (with welded-on grip ends). Center (top to bottom): notched edge-bend specimen, guided-bend specimen, shear-tension specimen, sheet-type tension specimen, and notched plate-type tension specimen. X1/5.



A. Back spalls in 0.305-inch-thick plate (Composite 9-10, Pack 65K).

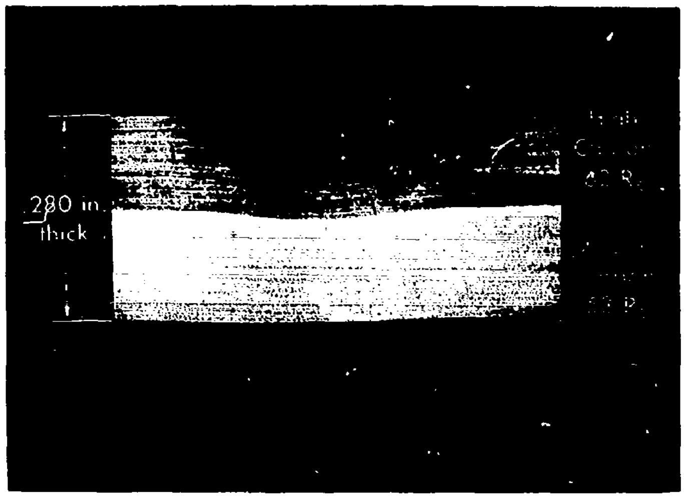


B. Excellent rear-face behavior in 0.290-inch-thick plate (Composite 20-21, Pack 66B).

Figure 33. Rear view of plate composites ballistically tested with caliber 0.30 AP M2 projectiles. About X2/3.

P-7112A-2
P-7112A-1

Figure 33A, B



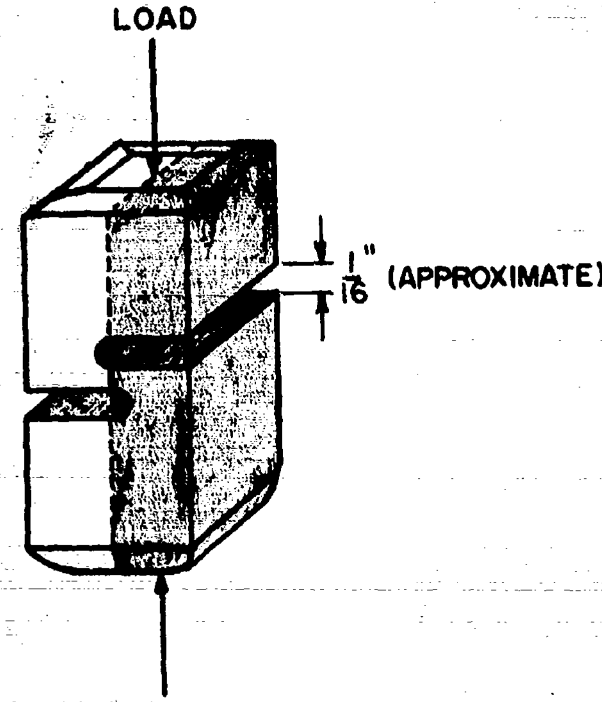
A. Excellent performance. Note how cracks are arrested by the rear plate. X1/3. AMRA photograph.

B. Back spall (see Figure 33A). High-carbon steel is the top layer. X5.

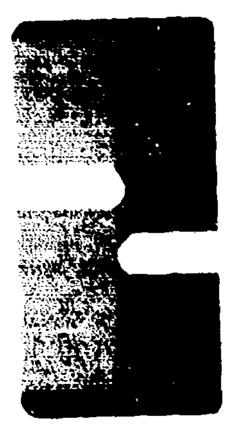
Figure 34. Macroetched cross-sectional views of projectile-impacted plates of Composite 9-10.

19856
18-606A-1

Figure 34A, B



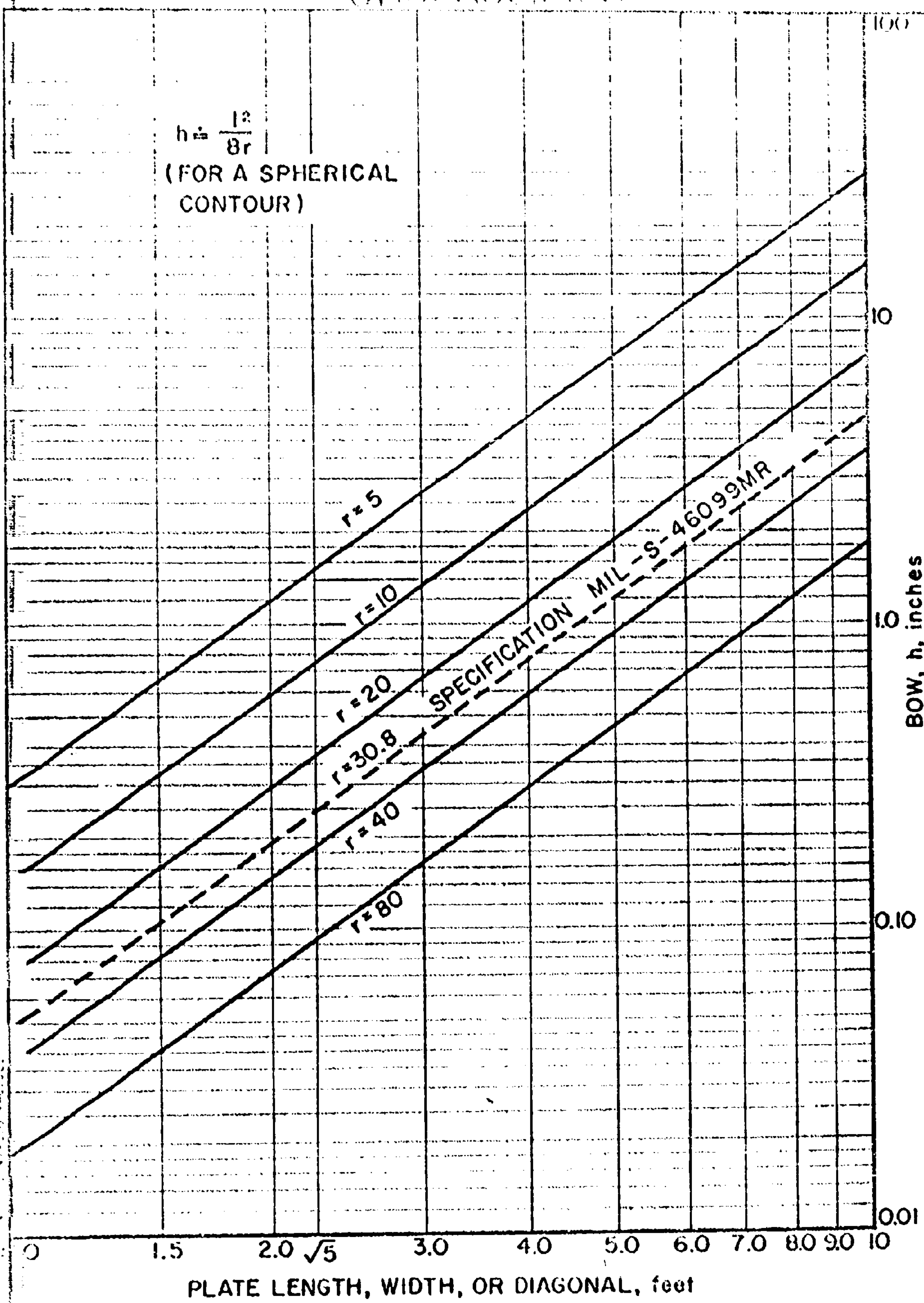
A. Sketch.



B. Photograph (macroetched specimen). X2.

Figure 35. Shear-compression specimen (full plate thickness).

FIGURE NO. 36



RELATION OF PLATE GEOMETRY TO AMOUNT OF BOW IN QUENCHED AND TEMPERED DUAL-HARDNESS STEEL ARMOR

FIGURE NO. 36

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Samuel J. Manganello and George C. Carter,
United States Steel Corporation, Applied Research Laboratory,
Monroeville, Pennsylvania 15146

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13. ABSTRACT (U) A research program was conducted to develop and optimize lightweight heat-treatable composite steel armor for protection against cal 0.30 and 0.50 AP M2 projectiles. Metallurgical, mechanical, and ballistic evaluations of plate composites indicated that (1) low-alloy (Ni-Cr-Mo) steels with about 0.55% C (front face) and 0.30% C (rear face) metallurgically bonded strongly in layer-thickness proportions of about 50% front-50% rear (cal 0.30 plates) or 40% front-60% rear (cal 0.50 plates) and heat-treated by quenching and tempering to hardnesses of about 60 R_C (front) and 50 R_C (rear) exhibited merit ratings of about 1.4; (2) higher merit ratings were obtained against cal 0.30 projectiles than against cal 0.50 projectiles; (3) higher merit ratings were obtained in production plates than in laboratory plates; (4) multilayer composites, although generally tougher, were no better than 2-layer composites in resistance to penetration by AP projectiles, and (5) a shear-compression specimen effectively measured the bond strength of dual-hardness steel plate composites. Seven production-size lots of roll-bonded dual-hardness steel armor have been made on existing facilities. Several large plates were supplied to AMRA. Production controls necessary to meet (or approach) the requirements in Specification MIL-S-46099A were determined. (Authors)

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